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Communication Protocols in Wireless Body Area Networks (WBAN)

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Sorbonne Université
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Communication Protocols in Wireless Body Area Networks (WBAN)

PRESENTED
BY
Wafa Badreddine Beji

FOR OBTAINING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN
COMPUTER SCIENCE, TELECOMMUNICATIONS AND ELECTRONICS
EN INFORMATIQUE

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Abstract

The rapid advances in sensors and ultra-low power wireless communication has enabled a new generation of wireless sensor networks: Wireless Body Area Networks (WBAN). WBAN [85] is a recent challenging area. There are several concerns in this area ranging from energy efficient communication to designing delay efficient protocols that support nodes dynamic induced by human body mobility.

In WBAN tiny devices are deployed in/on or around a human body, are able to detect and collect the physiological phenomena of the human body (such as: EEG, ECG, SpO₂, etc.), and transmit this information to a collector point (i.e *Sink*) that will process it, take decisions, alert or record.

WBAN differs from typical large-scale wireless sensor networks WSN [20] in many aspects: Network size is limited to a dozen of nodes, in-network mobility follows the body movements and the wireless channel has its specificities. Links have a very short range and a quality that varies with the wearer's posture. The transmission power is kept low to improve devices autonomy and reduce wearers electromagnetic exposition. Consequently, the effects of body absorption, reflections and interference cannot be neglected and it is difficult to maintain a direct link (one-hop) between the *Sink* and all WBAN nodes. Thus, multi-hop communication represents a viable alternative.

In this work we investigate energy-efficient multi-hop communication protocols in WBAN. Our work is part of SMART-BAN Self-organizing Mobility Aware, Reliable and Timely Body Area Networks project [6].

In order to evaluate our communication protocols described in the sequel in a specific WBAN scenario, we implemented them under the Omnet++ simulator [4] that we enriched with the Mixim project [109] and a realistic human body mobility and channel model issued from a recent research on biomedical and health informatics [89].

We are interested in WBAN where sensors are placed on the body. We focus on two communication primitives: broadcast and converge-cast.

For the broadcasting problem in WBAN, we analyze several broadcast strategies inspired from the area of DTN then we propose two novel broadcast strategies *MBP: Mixed Broadcast*

Protocol and Optimized Flooding:

- *MBP (Mixed Broadcast Protocol)*: We proposed this strategy in [28] as a mix between the *dissemination-based* and *knowledge-based* approaches.
- *OptFlood (Optimized Flooding)*: This strategy was proposed in [30] and takes into account the strengths and weaknesses of the basic strategy *Flooding*. *Optimized Flooding* is a revised version of *Flooding* whose purpose is to keep the good end-to-end delay given by *Flooding* while lowering energy consumption with the simplest way and the minimum cost.

Additionally, we performed investigations of independent interest related to the ability of all the studied strategies to ensure the FIFO order consistency property (i.e. packets are received in the order of their sending) when stressed with various transmission rates. These investigations open new and challenging research directions. With no exception, the existing flat broadcast strategies register a dramatic drop of performances when the transmission rate is superior to 11Kb/s.

There, we propose the first network-MAC layer broadcast protocol, *CLBP*, designed for multi-hop communication and resilient to human body postures and mobility. Our protocol is optimized to exploit the human body mobility by carefully choosing the most reliable communication paths in each studied posture. Moreover, our protocol includes a slot assignment mechanism that reduces the energy consumption, collisions, idle listening and overhearing. Additionally, *CLBP* includes a synchronization scheme that helps nodes to resynchronize with the *Sink* on the fly. Our protocol outperforms existing flat broadcast strategies in terms of percentage of covered nodes, energy consumption and correct reception of FIFO-ordered packets and maintains its good performances up to 190Kb/s transmission rates.

In the last part of the thesis, we concentrated on another communication primitive: the *convergecast* problem focusing only flat (i.e. non cross-layer) strategies. We proposed a classification of converge-cast strategies, adapted from DTN and WSN areas, in three different categories: *attenuation-based*, *gossip-based* and *multi-path-based* strategies. We then proposed a novel strategy called *Hybrid*. This work was published in [31]. We focused three parameters: resilience to the body mobility, end-to-end delay and energy consumption. Our novel strategy, *Hybrid*, behaves as a *multi-paths* strategy where messages are forwarded following pre-determined paths. However, in order to cope with postural mobility, our novel strategy will introduce messages broadcast.

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1

Introduction

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1.1 CONTEXT & MOTIVATION OF THE THESIS

Wireless Body Area Networks (WBAN) open a new area within Wireless Sensor Networks (WSN) research, in which invasive sensors with low computing power and limited battery life, deployed in/on or around human body, are able to detect and collect physiological phenomena of the human body (such as: EEG (Electroencephalography), ECG (Electrocardiography),

SpO₂, blood pressure, temperature, etc), and further transmit this information to a collector point (i.e *Sink* node) that will process it, take decisions or alert. In addition, movements can be tracked and predicted to help capturing motion with applications in virtual reality, gaming, sports as well as in detecting falls and accidents.

WBAN has a wide area of applications: remote health monitoring, military, security, sports and gaming. In particular, WBAN is a recent challenging area in the health monitoring domain. Outfitting patients with tiny, wearable, vital-signs sensors would allow continuous and long-term monitoring in their own homes.

There are several concerns in this area ranging from energy efficient communication to designing delays efficient protocols that support nodes' dynamic induced by human body mobility. In addition, to successfully deploy body area networks that can perform long-term and continuous healthcare monitoring, it is critical that the wearable devices be small and lightweight to avoid to be too intrusive on patient lifestyle.

WHY TODAY'S SENSORS ARE NOT ENOUGH ? Today, various types of sensors are already available. Connected wearable devices can measure various parameters and are widely used. Nevertheless, these devices are independent and are usually only connected to a central device such as a smartphone, which records data and uploads it to a cloud infrastructure. Devices do not communicate or collaborate together and neither can they take decisions or send requests to others. Hence, organizing the sensors in a network of collaborating devices would prevent the network from relying on a gateway that constitutes a single point of failure.

WHY WBANS ARE NOT WSN OR DTN NETWORKS ? Yet they differ in many aspects. The size of the network is limited to a dozen of nodes. Transmission power is usually kept as low as possible, not only to reduce interferences and to improve devices autonomy and lifetime, but also to reduce wearers exposure to electromagnetic signals and consequences from devices temperature. In addition, autonomy may be a critical factor to optimize when sensors are implanted. This results in creating short-range wireless links with a variable quality depending on the wearer's posture as much as on the environment. Sensor nodes are equipped with small batteries with limited capacity, hence, energy conservation is a critical issue for WBAN applications.

Short range transmission and postural movements in WBAN have a tremendous impact on the network partitioning implying a kind of body Delay Tolerant Network (DTN) [164, 162, 92]. DTN protocols seem particularly relevant in this context, as they are designed to tackle the intermittent connectivity and unpredictable signal attenuation. However, DTN usually suppose either an almost perfect knowledge of the mobility patterns or a fully random mobility.

In WBAN the body postural mobility do not match the mobility models usually considered in DTN hence the performance of the protocols proposed for DTN have poor results in WBAN.

TOWARDS MULTI-HOP COMMUNICATION Body absorption, reflections and interference cannot be neglected, and maintaining a direct one-hop link between a central node and all peripheral nodes is probably not the most effective strategy. However, in a multi-hop scenario, communication protocols would greatly benefit from taking into account the particular in-network mobility that results from the body movements. As communication is the most energy consuming operation that a sensor node performs, an efficient energy communication protocol is crucial to prolong the lifetime of the WBAN. Recent research [89, 149] advocates for using *multi-hop* communication in WBAN to guarantee low transmission power, low energy consumption and efficient routing. However, very few multi-hop communication protocols have been proposed so far and even fewer are optimized for the human body mobility. Multi-hop communication is therefore a viable alternative and most of the recent research in WBAN focuses on such communication protocols.

1.2 SMART-BAN PROJECT

This work is part of SMART-BAN, Self-organizing Mobility Aware, Reliable and Timely Body Area Networks, project [6]. SMART-BAN project aims to optimize the energy consumption of WBAN for medical applications. The project gathers researchers from different fields ranging from electromagnetic and communication theory to computer science. By undertaking a trans-disciplinary approach, the impact of physical layer will be taken into account in MAC and Network layers to draw fundamental energy limitations and to develop optimal communication strategies for reliably routing in medical body area networks.

The consortium (figure 1.1) is composed of the L2E (UPMC), specialists in communication channel design for embedded systems, and LIP6 (UPMC) and LTCI (Telecom ParisTech), specialists in the design of distributed protocols and network reliability. All together have the required multidisciplinary skills to address several issues in WBANs. Consortium fields of activity range from the Physical layer (L2E) to the Network and middleware layers (LIP6, LTCI), through the MAC layer (LTCI and LIP6).

1.2.1 CONTEXT & GOALS OF THE PROJECT

Medical sector is facing great challenges nowadays. Emergency departments today operate at over capacity [107]. Aging population requires also more healthcare. In a period of economical crisis, efficiency of the medical system needs to be increased significantly.

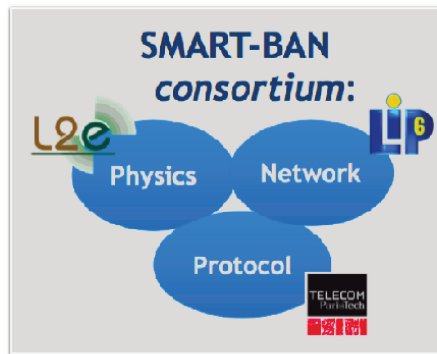


Figure 1.1: SMART-BAN consortium participants

To address these issues, recent years have witnessed the emergence of WBANs for medical applications. BANs are sensor networks that are embedded on the human body and provide useful healthcare monitoring such as EEG (Electroencephalography), ECG (Electrocardiography), EMG (Electromyography), blood pressure, glucose, etc. The use of wireless technology to interconnect sensors enables practical and seamless means to monitor patients. It thus can lead to more efficient patient’s management in hospital by automatically monitoring the vitals signs of many patients simultaneously to shorten patient’s wait-times. If BANs are connected to the Internet, they can also achieve continuous monitoring. This aspect has great outcomes since it is the key for fighting disease with a preventing approach and detecting at an early stage when a person’s health changes to the worse, thereby preventing emergency cases such as heart attacks. Continuous monitoring also represents a comfortable and effective economic way of taking care of age-related illnesses.

Consequently, Medical BANs (MBANs) have a huge potential and are expected to become a successful medical system that will help in solving the medical crisis and also in creating a new market in medical ICT (Information and Communication Technologies) [123]. In fact, the demand is so strong that in addition to already existing ISM (Industrial, Scientific and Medical) radio bands, an extra frequency band of 40 MHz (2.36-2.40 GHz) has been allocated in February 2013 in the spectrum (IEEE 802.15.4j, IEEE 802.15.6) specifically dedicated to low rate medical wireless BAN.

1.3 THESIS CONTRIBUTIONS & ORGANIZATION

In this work, we deal with small scale networks where the size of the network is limited to a dozen of nodes. We are interested in WBAN where sensors are placed on the body. In this type of networks sensors performances are tremendously influenced by the human body mobility and wearing clothes. Thus, we investigate two communication primitives: *Broadcast* and

converge-cast and the native capability of *multi-hop* protocols to handle reliable and energy-efficient communication within a such constrained network.

1.3.1 FIRST CONTRIBUTION: REALISTIC HUMAN BODY MOBILITY MODEL

In this work, we present a realistic human body mobility and channel model issued from a recent research on biomedical and health informatics published in [89] and described in details in chapter 2 section 2.7.2.

This channel model of an on-body 2.45 GHz channel between 7 nodes, that belong to the same WBAN, using small directional antennas modeled as if they were 1.5 cm away from the body. Nodes are assumed to be attached to the human body on the *head, chest, upper arm, wrist, navel, thigh, and ankle*. Considering the application of vital sensor monitoring for medical and health-care, these nodes are selected based on the possible vital sensors.

The nodes positions are calculated in 7 postures: *walking (walk), walking weakly (weak), running (run), sitting down (sit), wearing a jacket (wear), sleeping (sleep), and lying down (lie)*. Walk, weak, and run are variations of walking motions. Sit and lie are variations of up-and-down movement. Wear and sleep are relatively irregular postures and movements.

Channel attenuation is calculated between each couple of nodes for each of these positions as the average attenuation (in dB) and the standard deviation (in dBm). The model takes into account: the shadowing, reflection, diffraction, and scattering by body parts.

1.3.2 SECOND CONTRIBUTION: BROADCAST IN WBAN & FIFO ORDER CONSISTENCY OF BROADCAST PROTOCOLS IN WBAN

This contribution focuses on the broadcasting problem in WBAN and is presented in chapter 4.

When a node receives a packet, it needs to take a decision whether to forward it or not, to which of its neighbors and when. However, acquiring the necessary information on the nodes mobility is not free. It either requires a precise nodes localization mechanism, or requires to rely on *hello messages* to learn connection/disconnection patterns. In both cases the improvement realized by the mobility pattern characterization could be lost by the necessary control traffic. That's why we wished to compare various strategies with different levels of knowledge.

Hence, we investigate the native capability of *multi-hop broadcast* protocols, inspired from the area of DTN, to handle packets reception sent from *Sink* node within a such constrained network.

Our results show that existing research in DTN cannot be transposed without significant modifications in WBANs area. That is, existing broadcast strategies for DTN do not perform well with human body mobility. However, our extensive simulations give valuable insights and

directions for designing efficient broadcast in WBAN. Furthermore, we propose two novel broadcast strategies **MBP: Mixed Broadcast Protocol** (published in [28]) and **Optimized Flooding** (proposed in [30]) that outperform the existing ones in terms of end-to-end delay, network coverage and energy consumption. Additionally, we performed investigations of independent interest related to the ability of all the studied strategies to ensure the FIFO order consistency property when stressed with various transmission rates. These investigations open new and challenging research directions. With no exception, the existing flat broadcast strategies register a dramatic drop of performances when the transmission rate is superior to 11Kb/s.

1.3.3 THIRD CONTRIBUTION: CROSS LAYER APPROACH FOR BROADCAST IN WBAN

In chapter 5, we propose the first MAC-network layer broadcast protocol, **CLBP**, designed for multi-hop topologies and resilient to realistic human body postures and mobility.

CLPB is a slotted protocol that builds on top of pruned communication graphs constructed based of the channel model [89]. Our protocol is optimized to exploit the human body mobility by carefully choosing the most reliable communication paths in each studied posture. *CLPB* handles both the control medium access and the broadcast process. Moreover, our protocol includes a slot assignment mechanism that reduces the energy consumption, collisions, idle listening and overhearing. Additionally, *CLPB* includes a synchronization scheme that helps nodes to resynchronize with the *Sink* on the fly.

In order to include the channel model specificities in the broadcast process, *CLPB* needs a *preprocessing* phase that is handled at the *Sink* level. After this preprocessing phase, *Sink* broadcast packets that will carry both data and control information (e.g. slots assignment, synchronization information). Our new cross layer approach minimizes coordination overhead, no exchange of control packets because informations added to data packets are used as control informations and enable nodes to know everything about communication and traffic. Nodes alternate between: Reception, Sleep and Transmission modes. However, differently from other similar techniques, we strive to reduce the number of state switches and the duty cycle duration.

Our protocol outperforms existing flat broadcast strategies in terms of percentage of covered nodes, energy consumption and correct reception of FIFO-ordered packets (i.e. packets are received in the order of their sending). Furthermore, our protocol maintains its good performances up to 190Kb/s transmission rates.

1.3.4 FOURTH CONTRIBUTION: CONVERGE-CAST IN WBAN

In this part of the thesis, we concentrate on another communication primitive: the *converge-cast* problem focusing only flat (i.e. non cross-layer) strategies. We adapt from DTN and WSN areas representative converge-cast strategies and stressed them under realistic settings.

First, we propose a classification of the converge-cast strategies in three different categories: *attenuation-based*, *gossip-based* and *multi-path-based* strategies.

1. **Attenuation-based strategies:** In this category, nodes need a specific information in order to take the decision to either forward a message or to hold it. Moreover, nodes have to decide to which neighbor they will forward. According to the integrated mobility model, we will use, as information, the path loss value (*attenuation*) on links between each couple of nodes (similar to the way the classical geographical routing uses the distance to the *Sink*). The source S starts by broadcasting a request "AttREQ" asking its neighbors the attenuation value of their link with *Sink* node and sets a timer T .
2. **Gossip-based strategies:** In this category, nodes conduct a blind broadcast of messages in the network without relaying on any specific information. These strategies are inspired from broadcast strategies presented in [28].
3. **Multi-path based strategies:** In this category, we exploit predetermined paths (referring to nodes positions on human body) between the source and the *Sink*. Our choice is based on nodes' position on the human body. Contrary to the first category (attenuation-based strategies), here the choice is fixed all long the simulation. In this class nodes have up to two pre-selected privileged neighbors (call in the sequel parents).

Our extensive simulations prove that most of these strategies do not comply well with human body mobility. Thus, we propose a novel strategy called **Hybrid**. Our novel strategy, *Hybrid*, combines the advantages of both *multi-paths* and *gossip-based* strategies. It behaves as a *multi-paths* strategy where messages are forwarded following predetermined paths. However, in order to cope with postural mobility, our novel strategy will introduce broadcast. Indeed, nodes will first check links status with their parents before sending every data message. Hence, using these unique paths, *Hybrid* avoids packets loss.

We focused three parameters: Packet Delivery Ration (PDR), end-to-end delay and traffic load. *Hybrid* presents a good compromise in optimizing the three above evaluation criteria. This work was published in [31] and will be presented in chapter 3.

2

Wireless Body Area Network (WBAN): State of the art

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2.1 INTRODUCTION

The contribution of this chapter is to provide an overview of research conducted in WBAN.

WBAN was first presented by T. G. Zimmerman in an article from 1996, but he named these body networks as the Wireless Personal Area Network (WPAN) at the beginning [194]. Later on, PAN was redefined and the name WBAN evolved.

WBAN is a wireless communication network that takes human body as the center of the communication. Advances in microelectronics and integrated circuits, system on chip design, wireless communication and intelligent low-power sensors have empowered the development of WBAN. WBAN is considered as an evolution of wireless sensor networks towards wearable and implanted technologies and represent an increasingly important networking context. WBAN is seen as a valuable solution to monitor human body remotely and fluently.

Many works have discussed WBAN definitions, architectures, applications, etc [44, 114, 188, 40, 177, 184, 208, 116, 49, 105] because various current trends such as growing population have promoted the growth of WBAN. However, most of the existing works focus on theoretical performance enhancement.

IEEE 802 has established a Task Group called IEEE 802.15.6 in November 2007 for the standardization of WBAN. The purpose of the group is to establish a communication standard optimized for low power high reliability application for BANs [112].

We can find different annotations for WBAN like WBANS-Wireless Body Area Sensor Networks [200, 78] or WBSN-Wearable Body Sensors Network [82].

2.2 WBAN APPLICATIONS

Tiny sensors are deployed on the human body to collect vital signs and activity data (Table 2.1). WBAN has emerged as a key technology that operates in close vicinity to, on, or inside a human body and supports a variety of innovative and interesting applications that can be categorized into medical and non-medical applications [144]. WBAN has wide prospects in

health care, personal assistance, smart home, military, entertainments and sports, tracking and positioning field [122].

Vital sign	Position
Electroencephalogram (EEG)	head
Electrocardiogram (ECG)	chest, wrist
Respiration	chest
Pulse Oximetry	wrist
Blood Pressure	wrist, Upper arm
Glucose	wrist, navel
Temperature	wrist
Gyroscope-Accelerometer	all nodes
Electromyogram (EMG)	thigh, upper arm, wrist

Table 2.1: Vital sign vs node position (Source [89])

2.2.1 MEDICAL APPLICATIONS

Human health monitoring is considered as one of the most promising applications of WBAN [206, 225]. WBAN emerged as a viable solution in response to various disadvantages associated with wired sensors commonly used to monitor patients in hospitals and emergency rooms [47]. WBAN allows continuous monitoring of human's physiological parameters for further analysis while ensuring mobility and flexibility to patients while subtracting hospitalization costs. It also allows a clearer view to doctors of patient health's status (SpO₂ (Oxygen saturation), blood pressure, heart activity, body temperature, glucose level, etc) [158, 104]. Recent medical reports predict that the number of people using home health technologies or subject of remote health monitoring will enormously increase from 14.3 to 78 million consumers from 2014 to 2020 [60], respectively. Additionally, body sensors shipments will hit 3.1 million units every year. Hence, WBAN promises unobtrusive ambulatory health monitoring for extended periods of time and near real-time updates of patients' medical records. Researches show that most diseases can be prevented if abnormal symptoms were detected in their early stages as heart disease. Older people living alone or people with chronic diseases need ongoing surveillance. Medical tele-monitoring of these people allows a continuous disease control and prevention.

In medical applications, in addition of monitoring vital signs, WBAN provides assistance to automatic medical treatments or automatic dosing. Data are collected using different sensors attached to human body. These collected data are sent to medical unit which then decides the corresponding treatment method or the correct dosing to apply. For example, a pacemaker

which is an electronic device that helps person's heart to beat regularly or an insulin injector for a diabetes person.

In the sequel, we will realize through several references that researchers target most a medical context for WBAN.

2.2.2 NON-MEDICAL APPLICATIONS

Non-medical applications include gaming, sports, etc. For instance, in gaming and entertainment, sensors in WBAN collect coordinates movements of different body parts and make the movements of the character in the game e.g soccer player or tennis player. Thanks to WBAN, gaming becomes more interactive.

We also find WBAN in some critical jobs such as military, policemen or firemen. Thus, the observation of life signs and the surrounding environment will avoid mistakes, dangerous situations e.g in the case of fireman, the amount of oxygen, toxic gasses and the temperature are critical informations. In [24], Ben Arbia *et al.* evaluate the performance of multi-hop routing protocols while using different wireless technologies in an urban critical and emergency scenario. In the context of Public Safety Network (PSN), authors consider WBAN role as a key role to monitor the physiological status of the involved workforces and the surrounding environment.

2.3 WBAN ARCHITECTURES

2.3.1 WBAN COMPONENTS

Sensors collect physiological data and send them to the concerned entities. Then, diagnosis based on the received informations is performed and the right decisions are taken.

A three-tier architecture for a WBAN communication system can be proposed (figure 2.1):

Tier 1: Intra-WBAN communication Communication around the body of sensors between each others and communication between sensors and *Sink* node (PDA, phone, sensor, etc).

Tier 2: Inter-WBAN communication It is the communication between the *Sink* node and an access point. In inter-WBAN communication, a device coordinator *Sink* with specific features could be responsible to communicate with the adjacent WBANs. A coordinator is generally considered as a resource rich device, which can be a multi-standard node to interface with other technologies such as static WSN, WIFI access points or broadband cellular networks (4G, LTE, etc)

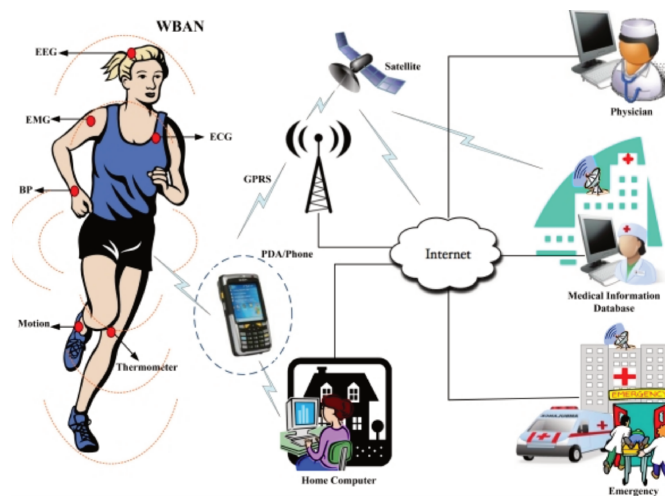


Figure 2.1: WBAN architecture [179]

Tier 3: Beyond-WBAN communication Connects to the inter-BAN through a gateway. Its functionalities are: database and data storage, remote access for medical stuff, etc. In [99], the system performs a real time analysis of sensors' data.

2.3.2 WBAN TYPE OF NODES

In WBAN, sensors are able to monitor, process and communicate various informations about human body and vital signs and give feedback to the user and to the medical entity.

Based on their functionalities, there are three types of nodes:

Sink or Coordinator Interface between users and sensors/actuators. It is the gateway between the WBAN and the external world or another WBAN. Several references [179] define it as a personal device (watch, phone, etc).

Sensors They measure body's parameters and then forward them. Sensors can be placed on or in human body. Sensors can be divided into two categories: end node and routers. End nodes accomplish their application and communicate directly with the gateway. Routers act as intermediate nodes which relay messages between other nodes and the gateway.

Actuators or actors Actuators are considered as smart sensors with electro-mechanical devices. For example, a system consists of a sensor to detect the blood sugar and an actor that delivers insulin.

2.3.3 WBAN COMMUNICATION STACK LAYERS

Physical Layer Radio propagation and mobility are particular in WBAN context compared with typical large scale sensors network. They are influenced by the characteristics and movement of the human body, indeed, the antenna is affected by wearer's posture and by sensors location (on-body, implanted). In addition, it is necessary to keep the transmission power at its minimum to save energy and limit interactions with the wearer. Three factors: Body Path-Loss (BPL), Receive Noise Figure (RNF) and Signal-to-Noise Ratio (SNR), affect the sensor node's transmission power when sending any data wirelessly. SNR is subject to communication link's quality. RNF is a factor that is device dependent. BPL is influenced by antenna in use and radiation pattern [80].

Some of the main responsibilities of the physical layer include frequency selection, signal detection, modulation, and encryption.

For on-body sensors, frequency bands are: 13.5 MHz, 5-50 MHz, 400 MHz, 600 MHz, 900 MHz, 2.4 GHz and 3.1-10.6 GHz. The Federal Communication Commission (FCC) has allotted the frequency band of 402-405 MHz for Medical Implant Communication Services (MICS) [143] as it is an ultra low power, un-licensed spectrum and won't cause interference to other users of radio spectrum.

Data link Layer This layer is responsible for multiplexing, frame detection, channel access and reliability.

At MAC layer, collision occurs when two or more nodes attempt to transmit at the same time. To ensure energy efficiency, MAC protocols propose to synchronize transmission schedule and listening periods to maximize throughput while reducing energy by turning off radios during sleep periods. There is a tradeoff between reliability, latency and energy consumption.

Network Layer Commonly, nodes in WBAN are not required to route the packets to other nodes. However, new researches show that multi-hop routing in WBAN is more adequate [150, 149] and is required to guarantee low transmission power low energy consumption and efficient data routing by distributing the routing load over the entire network.

In addition, routing is possible when multiple WBANs communicate with each other through their coordinators [58]. WBANs coordinators can exploit cooperative and multi-hop body-to-body communication to extend the end-to-end network connectivity.

2.4 CHALLENGES & OPPORTUNITIES IN WBAN

In order for WBANs to become ubiquitous and affordable, a number of challenging issues, such as standardization, system design, cost, compatibility, security and privacy must be resolved [83, 96].

As WBAN applications have diverse performance requirements [102], many of these requirements have not yet been addressed by the research community and challenges must be addressed before dealing with WBAN in daily life.

A number of health monitoring systems have been proposed. However, they rely on custom communication protocols and hardware designs, lacking generality and flexibility. The lack of standard platforms, system software support, and standards makes these systems expensive. Heavy sensors, high price, and frequent battery changes are all likely to limit user compliance.

Wired vs Wireless sensors Using wireless instead of wired communication decreases reliability and increases packets loss rate due to the characteristics of the wireless channel. However, the availability of a multi-path communication can partially remedy that.

Sensor hardware Sensors should be thin, small, ultra low power consumption and wireless enabled.

WBAN traffic Sensors collect and transmit to the concerned authority users' personal informations including sensitive and critical data.

There are different types of traffic [175]:

- On-demand traffic: initiated by *Sink* node to sensors on body. On demand traffic is further divided into continuous and discontinuous traffic. Continuous traffic is used in case of surgical event while discontinuous traffic is used in case of occasional information.
- Emergency traffic: is unpredictable and initiated by the sensor when there is an alert, an abnormal event usually detected when a threshold is exceeded.
- Normal traffic: is used for health monitoring where sensors forward collected data to the coordinator to be processed or forwarded to the corresponding authority.

Latency WBAN medical and non-medical applications require latency to be less than 125ms and 250ms respectively and jitter should be less than 50ms [142].

Mobility Data loss is high due to body movement that induces topology changes and links disappearance. Hence, to ensure the patient or wearer reliable monitoring, a specific

communication model adapted to human body mobility is needed. In the sequel, channel and mobility models for WBAN are discussed in details in section 2.7 and a specific channel and mobility model, integrated for the purpose of the communication protocols evaluation in WBAN, is described in paragraph 2.7.2.

Interference Communication in WBAN networks is highly constrained to different sources of interference. In [86], authors provide a study and analysis of coexistence issues and interference mitigation solutions in WBAN radio technologies that include IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee) and IEEE 802.11 (WiFi) which all use the same 2.4 GHz ISM band. While, in [142], authors discuss another source of interferences within multiple WBANs. Movassaghi *et al.* [142], divided interference mitigation schemes into two categories: interference reduction techniques (modulation scheme, data rate, etc.) and interference avoidance techniques (orthogonal channels assignment).

Transmission power Transmission range depends on sensors' transmission power. The increment of transmission power is not a convenient solution for WBAN. The latter is constrained by a threshold that complies with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6W/Kg in 1g of body tissue [181] and that protects the wearer from electromagnetic exposition, prolongs the lifetime of the WBAN network and ensures energy efficiency [34]. Several works discussed this issue in WBAN [220, 163, 160].

In [220], authors investigate the benefits and limitations of adaptive transmission power control in WBAN. Xiao *et al.* assume a high variation of links quality which motivated a dynamic transmission power control based on receiver feedback. Also, authors in [163, 160] propose a specific dynamic power control scheme that performs adaptive body posture inference for optimal power assignments.

In [146], authors proposed a protocol similar to store and forward mechanism and integrate to it a Transmit Power Adaptation (TPA) that controls transmission power consumption because all nodes know their neighbors which allow them to transmit data with minimum power and with a stable link quality.

In [122], average emission power density is equal to -45 dBm/MHz while in [82], transmission power is from -25 dBm to -20 dBm.

The proposed schemes in [220, 163, 160] focus on a star topology and do not consider multi-hop transmissions. In the sequel we will evaluate this important parameter in order to set it properly for sensor nodes.

Energy consumption & network lifetime Preserving sensors life time is a main concern in WBAN. Communication between sensors is considered the main factor of energy consumption and can be optimized at multiple layers of the communication stack. WBAN are supposed to operate properly for long duration of time without any battery recharge or placement especially for in-body i.e implanted sensors. Therefore energy management is one of the major concerns for WBAN protocols' design.

In [55], authors proposed a solution to minimize energy consumption. They deploy some non-sensing, dedicated nodes with additional energy source. This technique minimizes energy consumption of WBAN sensor nodes and enhances the network lifetime. However, additional hardware required for relay nodes increase the cost of the network.

Data security & privacy With the wireless communication, there are more security constraints than with wired communication. Sensors collect and transmit to the concerned authority users' personal informations including sensitive and critical data. These data require strict security mechanisms to prevent malicious use of them. Data security means data are securely stored and forwarded while privacy means that these informations are visible only to the authorized authorities [124].

Security services must also be guaranteed for WBAN network:

- Confidentiality: Data needs to always be kept confidential at a node or a local server. Data confidentiality should be resilient to device compromise attacks; that is, compromising one node won't help the attacker to gain the stored data at that node. For example, some WBAN applications require information about patient's location that attacker could use to track a patient.
- Integrity: Patient-related data is vital, and modified data would lead to disastrous consequences. Thus, data integrity shall be protected all the time including storage periods. For example, attackers could report false signals or replay old signals.
- Authentication: It confirms the identity of the original source node. The coordinator must have the capability to verify the original source of data. Data authentication can be achieved using a Message Authentication Code that is generally computed from the shared secret key.
- Availability: Patient's information should be kept available to the concerned entities. Node replication could be an interesting solution but not practical enough.

Authors in [61] present a method for making wireless body-worn medical sensors aware of the persons they belong to by combining body-coupled with wireless communication. This enables a user to create a wireless body sensor network by just sticking the

sensors to her body. A personal identifier allows sensors to annotate their readings with a user ID thereby ensuring safety in personal healthcare environments with multiple users.

Heterogeneous environment Sensors with different characteristics, computing power and available energy, could be deployed on the same WBAN. In our work, we consider an homogeneous environment where sensors characteristics are the same. Also we can consider data heterogeneity in WBAN. In [175], authors propose a routing protocol that can handle data heterogeneity, hence, depending on critical data, nodes decide when to transmit.

To address some of WBAN challenges, [98] propose a WBAN overall system while authors in [193] propose a WBAN prototype system designed both on hardware and software that includes physical, MAC and application layers based on IEEE 802.15.6 and a security module in addition. In [98], Jovanov *et al.* prototyped a WBAN utilizing a common wireless sensor platform with a ZigBee radio interface and a low-power micro-controller. The standard platform interfaces to custom sensor boards that are equipped with accelerometers for motion monitoring and a bio-amplifier for electrocardiogram or electromyogram monitoring. Software modules for on-board processing, communication, and network synchronization have been developed using the TinyOS operating system.

Other works in WBAN were interested in derived problems such as nodes localization [51, 155]. Nodes positions can be estimated through time-based ranging algorithms, for example by measuring the Round Trip Time of Flight of an impulse radio ultra Wideband (IR-UWB) that relies on two or three messages transactions. However nodes mobility and a 3 Way Ranging (3-WR) procedure could reduce this estimation accuracy. In [75], authors compares three localization estimation algorithms while taking into account MAC scheduling impact [76] and nodes mobility [74, 77]. However authors consider perfect channel and ignore the effect of shadowing and body obstruction.

2.5 WBAN vs WSN

WBAN differs from typical large-scale WSN [20, 101] in many aspects: the size of the network is limited to a dozen of nodes, in-network mobility follows the body movements and the wireless channel has its specificities. The communication links in WBAN have, in general, a very short range and a quality that varies with the wearer's posture, but remains low in the general case. WBAN has frequent topology changes and a higher moving speed whilst WSN has static and low mobility scenarios. The traditional WSN used for environmental monitor-

ing and home automation encounters many disadvantages when used for health monitoring because of WBAN limitations.

Table 2.2 bellow recaps WSN and WBAN difference characteristics.

Characteristics	WBAN	WSN
Number of nodes	limited to a dozen of nodes	large
Area of interest	small area	large area
Topology	variable due to body movement	static
Range	limited (human body in centimeters/meters)	large (monitored environment in meters/kilometers)
Need of Reliability	high	low
Need of delay	high	low
Security mechanism	strong to protect patient data	low
sensor's size	miniaturized	no matter

Table 2.2: Comparison of WBAN and WSN networks' characteristics

Due to their specific properties such as small size, data rate, reliability, security, mobility, power constraint, QoS requirement and heterogeneous traffic, WBANs require special protocols design to meet their particular needs. In other words, although WBANs derive from WSNs, there are intrinsic difference between these two networks.

2.6 STATE OF THE ART

2.6.1 MAC IN WBAN

In this section, we investigate several MAC protocols proposed for WBAN and highlights their features.

It is important to design efficient MAC protocols in WBAN to prolong the network lifetime and to ensure reliability. Several resources contribute to the inefficiency include collisions, overhearing, control packets overhead, traffic fluctuations and also the coexistence between WBAN and the other wireless systems.

The main schemes of MAC protocols are grouped into contention-based (CSMA) and scheduled-based or Contention free (TDMA) [71]. Frequency Division Multiple Access (FDMA) requires complex hardware while Code Division Multiple Access (CDMA) requires high computational demands.

Several CSMA-based MAC protocols, proposed for WSN have not proved to be energy efficient for WBANs while TDMA contention-free MAC protocols are unable to satisfy WBAN requirements [71].

At the data-link layer, energy can be saved by intelligent medium access control protocols that aim to turn the radio off whenever packet transmission or receipt is not expected. Several such MAC protocols have been developed in the literature [174, 166]: such as Preamble-based TDMA [205], Heartbeat Driven MAC (H-MAC) [121], Reservation-based Dynamic TDMA (DTDMA) [120], Distributed Queuing Body Area Network (DQBAN) [153], etc. In addition, several technologies such as Bluetooth especially Bluetooth Low Energy, Zigbee, IEEE 802.15.6 are targeting WBAN [81].

H-MAC [121] is a novel TDMA-based MAC protocol that aims to reduce energy consumption by exploiting heartbeat rhythm information to perform time synchronization.

AR-MAC [165]: authors proposed a MAC protocol for WBAN. First, they proposed a mathematical programming formulation based on [59]. Secondly, they implemented their protocol based on TDMA approach. A common problem in TDMA is the extra energy cost of the periodic synchronization. In order to avoid collision, they introduce DV (Drift Value) which is calculated based on the expected arrival time and the current arrival time. The drift value is incorporated in SYNC-ACK response.

In [133], the authors propose a MAC protocol for EEG remote monitoring application. The authors elaborate a TDMA based protocol in which they considered master-slave architecture and take advantage of the static nature of the body area network. In the master-slave architecture, they define a master node, a monitoring station and a sensor node. The basic idea is to use the monitoring station for coordinating the synchronization process and forward the collected data to the master node. The main drawback of this protocol is that a node needs to wait N cycles before resynchronization.

IEEE 802.15.4

The IEEE 802.15.4 is one of the most frequently used wireless technologies in WBANs by the research community [42] due to its performance, low power, low data rate and energy efficiency. IEEE802.15.4 can work on three different ISM frequencies and 27 channels. There are two types of nodes based on their features: RFD (Reduced Functions Device) and FFD (Full Functions Device). This standard supports peer to peer and star topologies. Different versions of IEEE 802.15.4 standard were proposed (IEEE 802.15.4j, IEEE802.15.4e,...). For example, in [141], authors use IEEE 802.15.4e for a cooperator-assisted WBAN.

In [201], authors presented a performance analysis of IEEE 802.15.4 standard in a star topology configuration. They focused their study on the beacon-enabled mode using slotted CSMA/CA. The aim of the study is to derive generic equations to model the average power consumption of a sensor. In beacon mode the super-frame is composed of two parts: the active period and the inactive period. The active one contains 16 slots and is divided into contention access period

(CAP) and contention free period (CFP). In CAP the slotted CSMA/CA is used for network formation. The CFP is used to achieve the real time constrained traffic such as video. The beacon is used by coordinator with aim to synchronize the end devices. The coordinator interacts with end devices during active period and may sleep in inactive period.

In [42], authors did study end-to-end delay, energy consumption and packets loss rate. They studied two parameters Beacon Order [O:14] and Super-frame Order [o:BO] which are set by the PAN coordinator (one PAN for star topology and several PAN for peer-to-peer topology). They described IEEE 802.15.4 mechanisms especially super-frame. SD (Superframe Duration) and BI (Beacon interval) are determined by BO and SO. BI is used so that nodes synchronize with the coordinator.

In [7], authors propose a time scheduling method based on IEEE 802.15.4 and implemented it on real hardware test-bed in order to decrease energy consumption.

IEEE 802.15.6

IEEE 802 has established a new task group called IEEE 802.15.6 for the standardization of WBAN [209, 111, 65]. The purpose of the group is to establish a communication standard optimized for low-power, short-range and wireless communication in the vicinity of, or inside human body to serve a variety of medical and non-medical applications. IEEE 802.15.6 standard was approved in 2012 and research on it is increasing in recent years while comparing between IEEE 802.15.4 and IEEE 801.15.6 [66].

IEEE 802.15.6 defines three physical layer: Narrowband (NB), Ultra Wide Band (UWB) and Human Body Communications (HBC). The selection of the physical layer depends on the application requirements. IEEE 802.15.6 has basically introduced the basics HBC [100, 132]. In addition, IEEE 802.15.6 [192] provides support for quality of service such as emergency messaging, a strong security and data rates up to 10 Mbps. The coordinator divides the entire channel into super-frames for referenced resources allocation. Each super-frame starts by broadcasting a beacon packet which consists of information for establishing link and synchronization. To support traffic differentiation, the IEEE 802.15.6 standard specified a user priority field in WBANs frame structure. For data frames, this field can take seven different values: 7 for emergency or event report; 6 for medical data; 3 for controlled load.

UWB PHY is more robust to the channel variations and operates at very low power levels than narrowband [48]. In addition, IR-UWB (Impulse Radio-Ultra Wide Band) consists of the default and high quality service physical layer options for general and high priority medical applications. Physical layer options allow for a set of different modulation and coding techniques to obtain various data rates. Hence, many researches on IEEE 802.15.6 were proposed.

In [140], authors propose a novel link adaptation mechanism to coordinate available data rates in an optimal manner and maximize energy efficiency in IEEE 802.15.6 IR-UWB.

A sophisticated MAC protocol that controls access to channel is defined on top of the physical layer. The MAC layer defined in IEEE 802.15.6 includes frame processing, access model, power management, clock synchronization, etc [112]. Considering inter-BAN interference, based on IEEE 802.15.6 standard, nodes in a single WBAN can avoid interference by using multiple access techniques such as time division.

In [207], a throughput and delay analysis of IEEE 802.15.6-based CSMA/CA protocol is conducted, while in [87], a power efficient mechanism is proposed.

SYNTHESIS

MAC protocols play an important role in ensuring an efficient communication in WBAN. Many protocols have been proposed, however, these protocols are inadequate to WBAN characteristics especially to the instantaneous human body mobility.

Despite that IEEE 802.15.6 standard was specially proposed for WBAN, few works have discussed IEEE 802.15.6 implementation [193, 136, 226]. None of the above implementations evolve a complete WBAN system based on IEEE 802.15.6. For example, in [73], authors implement only IEEE 802.15.6 beacon mode with superframes. Beacons need to be received by all nodes in the network to enable the connection. Indeed, the topology supported by IEEE 802.15.6 standard is star topology and frame exchanges occur directly between nodes and a hub. Even if two-hop cooperative communication is included as an option in the IEEE 802.15.6 standard, in reality, data exchange between the hub and each node is accomplished via a round-robin approach which results in a two-hop star topology.

In the sequel, our work is based on IEEE 802.15.4 CSMA/CA non-beacon mode. IEEE 802.15.4 standard ensures low power, reliable and short range radio communication. It supports star, peer-to-peer and mesh topologies. In addition, complete implementations of this standard are available, for example with MiXiM framework [2].

2.6.2 ROUTING IN WBAN

Routing in WBAN is an important challenge especially in critical and emergency situations that attracted significant research interest [143, 22]. Several routing protocols have been proposed in the past decade [62]. Most protocols are adaptations of classical strategies to the WBAN context. A main concern in WBAN is to use least power to transmit data from sensors to *Sink* or vice versa. Thus, an efficient routing protocol is essential to overcome this issue. A comparative analysis of energy efficient routing in WBAN is presented in [19]. The comparison can be done based on various parameters and routing protocols can be classified with respect to their

aims in different categories [144]: QoS-based routing protocols, temperature-based routing protocols (in-body), cross-layer-based, cluster-based routing protocols. In addition, they can be classified into: intra-WBAN and Inter-WBAN routing protocols.

QoS AWARE ROUTING PROTOCOLS

QoS aware routing protocols aim to provide better service to selected network traffic in WBAN. Protocols' design [127, 54, 126] focuses on modular architecture where different modules coordinate with each other to provide QoS services. Thus routes are chosen in accordance with traffic priorities and more reliable routes are granted to highest priority packets.

DMQoS [167] is a modular QoS based protocol. It sets up a modular architecture wherein different modules coordinate with each other to provide QoS preferment services. DMQoS classifies data into four main categories: ordinary, critical, delay driven and reliability driven packets. The routings of delay critical and reliability critical packets are handled separately by employing independent modules for each, whereas for the most critical packets having both stringent delay and reliability constraints, the corresponding modules operate in coordination to guarantee the required service. The reliability control module injects minimal redundant information by exploiting high reliability links. To ensure reliability, DMQoS duplicates transmitted data packets, which leads to energy consumption and interference increase.

Zahoor *et al.* present an energy and QoS-aware routing protocol (ZEQoS) [106]. It provides service differentiation through classifying traffic into three categories: ordinary packets (OPs), delay-sensitive packets (DSPs), and reliability-sensitive packets (RSPs), then determines an end-to-end route that ensures the satisfying of QoS parameters based on respective traffic type. ZEQoS introduces two main modules (MAC layer and network layer) and three algorithms (neighbor table constructor, routing table constructor and path selector). Extensive simulations using OMNeT++ based simulator Castalia 3.2 demonstrate that the performance of the proposed integrated algorithm is satisfactory when tested on a real hospital scenario. Simulations also show that the ZEQoS also offers better performance in terms of higher throughput, less packets dropped on MAC and network layers, and lower network traffic than comparable protocols including DMQoS [167].

These protocols provide different modules for different metrics. Hence, they ensure high reliability, low delay but high numbers of packets.

THERMAL AWARE ROUTING PROTOCOLS

Temperature rise of devices due to processing and communication may be dangerous for surrounding tissues and harms human body. In addition, a high temperature may damage devices

from a long-term monitoring. Hence, a series of protocols [94, 32] were proposed in order to reduce the heat generated by devices.

Thermal aware routing protocols are designed to support temperature rise up to a predefined threshold, that is, data transmission among the sensors should disperse around networks and not rely on only one route.

Several thermal-aware routing protocols use thermal-aware technology [185]. The latter computes temperature changes of human tissues surrounding the sensor nodes. This temperature prediction model is constructed using FDTD technique. Protocols compute the SAR: Specific Absorption Rate in W/kg [33] and the rate of rise of temperature.

TARA-Thermal-Aware Routing Algorithm [199] is the first routing protocol which focuses on the temperature rise problem. If the temperature of any node is higher than a threshold, then, this node is kept isolated from the network until it returns to its normal state. TARA is a knowledge-based routing protocol where each node exchanges a routing table with neighboring nodes.

TSHR-Thermal-aware Shortest Hop Routing [14] is based on a shortest path routing. Nodes route packets to the next hop belonging to the shortest path even if this next hop's temperature exceeds the fixed threshold. Another dynamic threshold is defined which defines hot spot.

M-ATTEMPT for Mobility-supporting Adaptive Threshold-based Thermal-Aware Energy-efficient Multi-hop Protocol [93] is an energy efficient and thermal aware routing protocol. The selection of routes is based on nodes' energy consumption and data rate. In the network design, high data rate nodes communicate directly with the *Sink* (single-hop). For critical data packets they increase their communication power while for ordinary data packets multi-hop communication is used. At the beginning, all sensor nodes send a hello packet containing information about their neighbors and distance to *Sink* node in terms of hop count, then in routing phase routes with minimum hop-counts are chosen within the existing routes. *Sink* node creates TDMA schedule for normal data delivery transfer after routes are established. If multiple next-hop neighbor nodes have the same hop count then the neighbor node with the minimum energy consumption to the *Sink* is chosen. When a node reaches temperature threshold, it returns packets to previous node and breaks down its connection with its neighbors while the children nodes select another optimal route. The main drawback of this protocol is when a node is disconnected from its current parent, it will be affected a new parent which will introduce extra energy consumption and delay. In [224], authors propose a routing protocol with mobility support CEMob which is an improvement of [93]. The proposed routing strategy is based on a minimum hop counts metric. They exploited single hop and multi-hop communications for data differentiation i.e normal and emergency data.

While these protocols limit heating effects on the human body and radiation absorption, they overlook reliability and network lifetime.

CLUSTER BASED ROUTING PROTOCOLS

In clustering, network is divided into non-overlapping sub-networks/clusters where each cluster has a cluster head responsible to collect the sensed data from its cluster and forward them to the *Sink* node.

Clustering protocols distinguish themselves by how they elect cluster heads. In [139], for instance, nodes with highest local density are chosen as cluster heads. Once clusters are built, routing is done in a hierarchical way managed by cluster heads.

In [13], authors present DSAB – Dual Sink Approach in WBANs. DSAB protocol uses a clustering technique to improve routing scheme performance with the use of two *Sink* nodes as cluster heads. The protocol starts with an initialization phase where sinks broadcast Hello packets with their IDs and location then nodes reply with their IDs, locations and energy level. Based on these informations, a cluster formation is processed and a time slots allocation using TDMA MAC protocol is established by CHs. However if data is not critical, a forwarder selection is processed based on SNR threshold, residual energy, transmission power and distance from *Sink* node. Mobility was not considered in the performance evaluation.

In [183], Sethi *et al.* propose Energy Efficient and Reliable Data Transfer (EERDT) Protocol for WBAN. EERDT algorithm use an hierarchical routing. A one-hop routing is used for important data transfer. A cluster head election is conducted based on a cost function related to each node energy reserve. Remaining nodes will choose the closest (minimum distance) cluster head to forward data to. However, a periodic update is needed.

In [203], a CH is selected as a node having maximum energy. A schedule is shared by CH to remaining nodes for transmitting their data.

CBBAP-Cluster Based Body Area Protocol enhances the overall energy [18] where cluster heads are selected based on the neighboring nodes and intend to reduce transmission distance. The throughput aims to increase due to an efficient routing maintenance.

Anybody [219] has features to restrict the sensor nodes to transmit directly to the *Sink* and improves the efficiency of network by changing the selection criteria during the cluster heads selection mechanism. In [219], authors propose a Hybrid Indirect Transmission (HIT) data gathering protocol, which combines clustering with forming chains.

Both [219, 139] have improved network lifetime however the ned to end delay and the reliability constraints in those latter are not optimized for WBAN which lead these protocols to be more suitable for sensor networks.

Clustering in WBAN network, is not adapted for WBAN especially because of the limited number of nodes and the instantaneous human body mobility.

CROSS-LAYER BASED ROUTING PROTOCOLS

Other researches focused on cross-layer challenges and limitations in WBAN [46] and the role of each layer to optimize the overall network performance when invoking cross-layer design [204]. For example, the MAC slot allocation can be customized for the underlying routing tree, thus providing routing specific energy economy at the MAC layer while handling body mobility by adaptively reconstructing and maintaining the tree topology used for packets routing.

In [36], authors proposed WASP-Wireless Autonomous Spanning tree Protocol, a converge-cast cross-layer protocol. WASP is a slotted protocol, time axis is divided into contention free and contention based slots grouped in cycles, that uses a spanning tree for medium access coordination and traffic routing. Each node will transmit to its children in which slot they can send their data using a special packet called WASP-scheme. Each node has a unique WASP-scheme constructed based on its parent scheme. WASP-scheme is also used as acknowledgement to each node's parent and as resources request if needed. Hence, WASP-scheme contains: sender node address, slots already allocated to the children of the parent node, silent period interval, forwarding received data to the *Sink*, contention slot, acknowledgment order. These messages permit traffic control and rise resource request from parents of children which minimize the coordination overhead. In addition, a WASP-Cycle deliver traffic routing and medium access coordination using the same spanning tree which results in lower energy consumption and higher throughput

In [68], authors implement WASP and give valuable results. Results show that WASP accomplishes maximum packet delivery ratio, little energy consumption and low end to end delay. Though, WASP does not consider quality of link. Note that for some parent nodes sleep period is shorter because they have to handle more children than other parent node, hence power balancing issue is not discussed. Also, WASP is not resilient to realistic human body mobility.

CICADA, [115], was proposed as an improvement of WASP [36]. CICADA aims to reduce energy consumption with the use of a spanning tree and an assignment of transmission slots using Time Division Multiple Access (TDMA) scheduling. This protocol setups a network tree in a distributed manner and parents nodes are responsible for telling their children when they can communicate and also collect data from their children nodes and relay to *Sink* node. Nodes can sleep in slots, where they are not transmitting or receiving. Each cycle is divided into sub-cycles: one is the control sub-cycle and the second is the data sub-cycle. During the control sub-cycle, the children nodes send to their parents their control scheme, the length of the control sub-cycle and depth of the tree. In the data sub-cycle, child node sends data packets to their parent node. To join the tree each data sub-cycle has a slot for new nodes. After hearing

the data scheme of the desired parent node, each new child node is allowed to send JOIN-REQUEST message in that slot. However, their proposed protocol only support node to *Sink* traffic (converge-cast), its adaptation to broadcast was reported as open question. In addition, CICADA wasn't evaluated against realistic human body mobility and high transmission rates. A cross layer secure low-delay for multi-hop WBAN was proposed in [186, 187].

WASP and CICADA do not consider balance power consumption among interconnected nodes missing an important aspect of energy efficient communication.

A similar approach is proposed [148] where authors introduce SIMPLE – Stable Increasing-throughput Multi-hop Protocol for Link Efficiency in WBAN. A cost function is used to select the parent node with high residual energy and minimal distance to the *Sink* node. This parent acts as forwarder to transmit data to the *Sink* node. The system model consider sensor nodes with equal power and computational capabilities. The protocol works in three phases an initial phase where *Sink* node broadcasts a packet that contains its position while the other nodes broadcast a packet that contains their ID, position and energy status, a next hop selection phase where *Sink* node computes the cost function of each node based on the received information from the hello packet and nodes with minimum cost function are selected as forwarder, then, a scheduling phase where forwarder nodes assigns TDMA schedule to other nodes hence nodes with data to transmit wakes up only in their assigned time slot. However, collecting data from all nodes results in increasing transmission delay to *Sink* node.

In [9], authors present a Cross-layer Opportunistic MAC/ Routing (COMR) protocol for multi-hop WBAN. COMR discusses relay nodes importance and its criteria. An election algorithm, using a timer based approach, based on a four-way handshake RTS/CTS and acknowledgments. The value of the timer depends on its RSSI (Received Signal Strength Indicator) and residual energy. However, the evaluation was made using a static network topology. As an extension, in [26], the performance of COMR protocol is investigated taking into account a mobility model with two scenarios: standing and walking and the impact of varying payload sizes. However, authors consider each node speed independently from the others nodes.

2.6.3 EVALUATION TOOLS

In this section, a brief description of different simulation tools is presented. There is a large number of network simulators that can be found in the literature.

SIMULATORS

Omnet - Objective Modular Network Test-bed in C++ [4, 212] Omnet is a discrete event simulator built in C++, extensible, supports module programming model, component-based simulator in which a number of libraries and frameworks are available. Most

frameworks and simulation models are open source. Authors in [213] present an overview of Omnet++ simulator. It provides the basic tools to run simulations and can be used for wired and wireless areas. A simulation model consists of modules. Modules are communicating FSMs that communicate by passing messages over connections (links), the reception of a message is an event and connections are defined using the NED (Network topology Description) language (figure 2.2). Thanks to an interactive Graphical User Interface (GUI), Omnet++ offers an easy tracing and debugging tool.

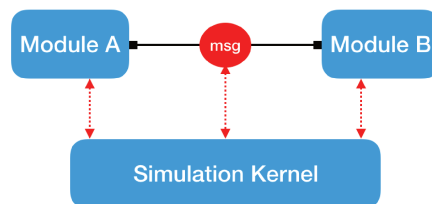


Figure 2.2: Message passing in Omnet++ simulator

WSNet WSNet is an event-based packet-oriented network simulator. The simulated nodes are built with hardware components, a software component for the behavior and resources. In [17], authors propose an adaptation to WSNet simulator to BAN and BBN contexts in order to fulfill the upper layers' requirements (MAC, network and application layers).

NS-3 NS-3 [3] is an open-source and discrete event simulator which was first developed in 2006. NS-3 is not an extension of NS-2. Both simulators are written in C++ but NS-3 does not support NS-2 APIs. There are few studies [131, 11] using NS-2 or NS-3 for BAN studies. In addition, these studies are based on unrealistic BAN channel models which impact the interference evaluation.

OPNET - Optimized Performance Network Engineering Tool Opnet [5] is a widely used general wireless network simulator. BAN-specific coexistence is studied in [53, 52]. However, the simulator does not consider the particularities of BAN propagation.

FRAMEWORKS

The most relevant frameworks for BAN are MiXiM [2] and Castalia [1].

Mixim Mixim is an OMNET++ modeling framework for mobile and fixed wireless networks [118, 109]. Mixim concentrates mainly on the physical layer of the protocol stack and offers detailed models of radio wave propagation, interference estimation, radio transceiver

power consumption and mobility models. In addition, the integration of different mobility models, example MoBAN makes it more realistic option to simulate low layers (PHY and MAC).

Castalia Castalia is based on OMNeT++ platform and is developed for networks of low power devices such as wireless sensor nodes. The main advantages are advanced channel model based on empirically measured data and radio model based on real radios for low-power communication and monitoring of the power consumption.

WBAN IMPLEMENTATIONS

Different implementations of WBAN [73, 43] were proposed for WBAN.

In [73], authors present an implementation of WBAN module in the NS-2 (Network Simulator) simulator based on IEEE 802.15.6 standard. The implemented module comprises functions of MAC management and data exchange. This module is based on IEEE 802.15.6 beacon mode with super-frames, which means beacon frames will be broadcasted to nodes to enable the connection and announce the access phases. In addition the topology adapted is one-hop star topology and CSMA/CA scheme is chosen to access the channel.

In [43], authors propose a cooperative software-hardware approach for WBAN implementation based on IEEE 802.15.4 that decreases the time and complexity of system design and implementation. This framework consists of a software WBAN simulator, WBAN hardware platform and code generator for sensor nodes. The proposed framework is convenient for design and verification of WBAN communication protocols and applications efficiently and details hardware design so the hardware of the sensor nodes is transparent to users.

2.6.4 COMMUNICATION PROTOCOLS PERFORMANCE EVALUATION SETTINGS

We choose to work with Omnet++ simulator. Omnet++ is a well structured and highly modular simulator that allows us to focus on network layer as shown in figure 2.3 and on implementing message exchange between entities. In addition, Omnet++ defines its own NED language to handle interactions between the different (sub-)modules for the purpose of the evaluation. It also has a good visualization and results analysis tool.

Omnet++ is then enriched with MiXiM framework. Comparing to Castalia framework, MIXIM offers a complete implementation of radio models in addition of a better community support.

We implement several communication protocols and evaluate them under realistic WBAN settings. For evaluation, we focused the reliability (Packet Delivery Ratio (PDR)), the end-to-end delay and nodes' energy consumption. To do so, we principally exploit, as shown in

figure 2.3, the physical layer for integrating the realistic channel and mobility model for WBAN (presented in details in section 2.7.2) and the network layer for protocols implementation.

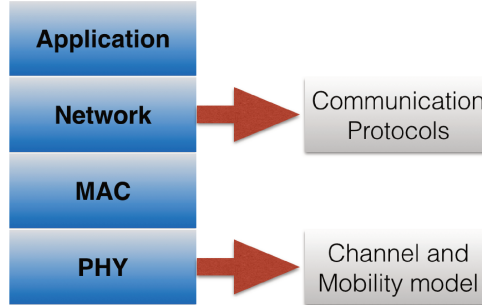


Figure 2.3: Thesis contributions in accordance with protocol stack

In the sequel, we study two communication primitives: Broadcast (chapters 4 and) and converge-cast (chapter 3).

We choose Omnet++ (presented in section 2.6.3) as simulator to evaluate our contributions (version 4.6). The simulation model is described all along the manuscript, starting, in this chapter, with the chosen framework Mixim [109] and the mobility model described in section 2.7.2.

Table 2.3 gives an overview of protocols' implementation by describing Omnet++ main configuration files.

File extension	Description
.ned	Defines modules and network topology using NED language
.msg	Defines messages' fields. Messages are handled in a module by the method handleMessage (cMessages *msg) and sent to other modules by the method send(cMessage *msg)
.cc	Implements the behavior of communication protocols
omnetpp.ini	Defines simulation parameters: network configuration, ned files, random number generator
.sca	Procedure Finish() is called at the end of a simulation to record scalar statistics in an .sca file

Table 2.3: Omnet++ configuration files

We can start several runs. The number of RNGs is set in the .ini file, and using multiple RNGs avoid unwanted correlation. Seeds are automatically selected based on RNG number and run number. The standard Random Number Generator RNG: Mersenne Twister with a period of $2^{19937}-1$. There are several predefined distribution (uniform, exponential, normal, etc).

In addition, for simulations, we can specify user interface for run: Tkenv for the GUI (default) or Cmdenv for the command line.

The energy parameters are hardware dependent. In our simulations, the transceiver Chipcon CC2420 were considered having low power and are frequently used in WBAN applications.

2.7 MOBILITY & CHANNEL MODELS IN WBAN

The characterization of the physical network layer is an important step in the design of a WBAN system. Different factors influence channel model like the environment where users are located, nodes' position and wearer's postures (walking, running, sleeping,...), etc. Wireless links are not stable and may appear and disappear according to a pattern that depends on these factors.

Mobility in WBAN has some specific characteristics that makes this network different from other categories of wireless multi-hop networks and the nature of the propagation of electromagnetic signals in complex shaped human body is different from other environments. Hence, several mobility models proposed in the literature for WSN and Ad hoc networks (Random Walk Mobility model and Random Waypoint mobility model [25], Reference Point group mobility model) are not suitable for WBAN due to their different movement patterns.

There is a need to comprehend the characterization of WBAN channel models under varied channel conditions. So in order to design a high quality WBAN, it is important to examine and improve the propagation characteristics of channel models of WBAN. Naganawa *et al.* [89] modeled a 2.45 GHz WBAN channel over 7 links between on-body nodes equipped with 5mm dipole antennas. Figure 2.4 illustrates the variability in links characteristics by showing the density function of the path loss for two of these links in different positions. Nodes would rather use links that are strong, i.e. exhibit a low average path loss, and reliable, i.e. have a low variance. However, a position change may increase the variance significantly and there is no guarantee that the network may remain connected with only low variance links.

Models can be used by manufacturers to validate the performance of WBAN systems using well specified setups, to investigate different issues like the use of a single-hop or multi-hop communications or for high layer designs where protocols can be performed using the physical-layer models.

In [180], authors propose a mobility model for the movement of nodes placed on the human body by calculating the distance between *Sink* node and sensor nodes when human body is in movement. Authors start by selecting the actual posture and use probabilities for changes from a posture to another one. Then, regarding each posture, a detailed description is given for the latter and the distance between *Sink* node and the other nodes on the body is calculated. For example, for standing posture, authors consider distance between *Sink* node and all the

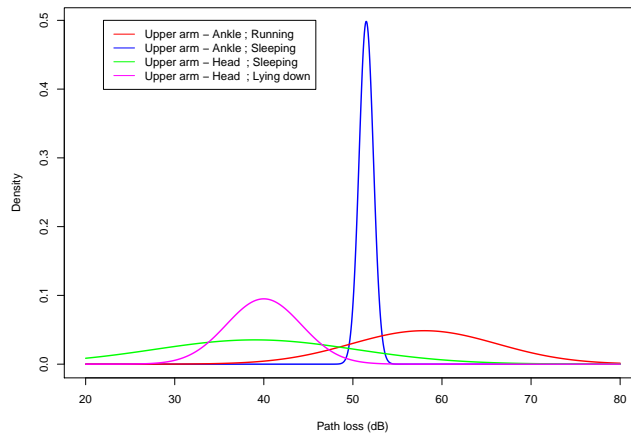


Figure 2.4: PDF of the path loss between upper arm node and other nodes in different positions (Data source [89])

other nodes constant. While for the other postures, authors use mathematical formulas for calculating the distance.

In [169], measurements are performed on a real human using half-wavelength dipoles. The measurements results are compared with FDTD simulations. Even if simulations agreed with measurements, the path loss models are low representative for the human body mobility.

Authors in [194] provide an overview of different channel models and characteristics of WBANs.

Model types Two types of model can be generated: a theoretical or mathematical model which is based on the fundamental principles of electromagnetic propagation and will permit a precise modeling of a specific situation at radio link level and requires a detailed description of the propagation environment, and an empirical model which is a set of propagation measurements and provide a convenient basis for statistical modeling of the channel.

Fading Propagation paths can experience fading due to different reasons such as energy absorption reflection, diffraction, shadowing by body and body posture. The other possible reasons for fading is multi-path due to the environment around the body. Fading can be categorized into small-scale fading (rapid fluctuations in the amplitude and phase of the received signal within a small local area in a small period of time due to small changes in location of the on-body devices or body positions) and large scale fading (refers to signal attenuation due to mobility over larger areas and it occurs due to variation in distance covered by signal between antenna positioned on the body and external node because of diffraction from large surrounding objects).

Path Loss In WBAN, path loss is both distance and frequency dependent. The path loss between the transmitting and the receiving antennas is a function of the distance d . Based on Friis formula in free space path loss in dB is expressed as follows in equation 2.1:

$$PL(d) = PL_0 + 10 * n * \log\left(\frac{d}{d_0}\right) \quad (2.1)$$

Where PL_0 is the path loss at a reference distance d_0 , and n is the path loss exponent. The greater the distance is, the more important the attenuation is.

Shadowing Shadowing is the process of blocking a signal by large objects which are encountered due to the variation in the environment surrounding the body or even due to the movement of the body parts. It causes variation in path loss of signal from that of mean value for a given distance. When considering shadowing, the total path loss can be expressed by equation 2.2

$$PL(d) = PL_0 + S \quad (2.2)$$

Combining equations 2.1 and 2.2, the total path loss is presented by equation 2.3

$$PL(d) = PL_0 + 10 * n * \log\left(\frac{d}{d_0}\right) + S \quad (2.3)$$

Power Delay Profile Because of multi-path reflections, the channel response of a BAN channel looks like a series of pulses. In practice the number of pulses that can be distinguished is very large and depends on the time resolution of the measurement system. The power delay profile of the channel is an average power of the signal as a function of the delay with respect to the first arrival path.

Channel models parameters are extracted using: FDTD analysis, measurements or measured CTF.

In [195], authors provide stochastic channel models for wireless body area network (WBAN) on the human body. Parameters for the channel models are extracted from measured CTF (Channel Transfer Function) by a Vector Network Analyzer (VNA) in a hospital room. The measured frequencies are 400MHz, 600MHz, 900MHz and 2.4GHz and UWB.

In [64, 230], path loss models in the Ultra Wide Band (UWB) bands were shown through FDTD analysis. In [173], path loss models are extracted from measurements results for frequency bands of 400MHz, 900MHz and 2.4GHz

The MoBAN [147] framework for Omnet++ adds mobility models for WBAN composed of 12 nodes in 4 different postures. Unfortunately the MoBAN code mainly focuses on the

mobility resulting from the change of position, rather than describing coherent and continuous movements. Besides, it models the movement of each node with respect to the centroid of the body and the signal attenuation between couples of nodes is approximated with a simple propagation formula that is not accurate enough to model low-power on-body transmission. It neither models absorption and reflection effects due to the body, nor alterations due to the presence of clothes or interference from other technologies at the same frequency since 2.4 GHz is a crowded band.

Also postures' detection were discussed. For example, in [130], authors collect multi-modal sensor data from strategically placed wireless sensors over a human body and process that using a Hidden Markov Model (HMM) in order to identify the subject's instantaneous physical context. Sensors modalities are acceleration, proximity (using RSSI) and orientation. A low RSSI indicates a high signal strength and that body parts are positioned close to each other like during sitting posture.

At the end, our goal is to point out the impact of body mobility in trading off reliability, energy efficiency at sensor nodes.

2.7.1 WBAN ARCHITECTURE BASED ON SENSORS' POSITION

WBAN can be categorized to in-body or on-body networks.

In on-body networks [154], wearable sensors communicate to a *Sink*/gateway and are placed approximatively 2cm away from it. On-body network are used for many applications: medical, gaming or multimedia applications. This network can have different topologies: star, tree or mesh. Figure 2.5 shows the different topologies while sensors are deployed on a human body.

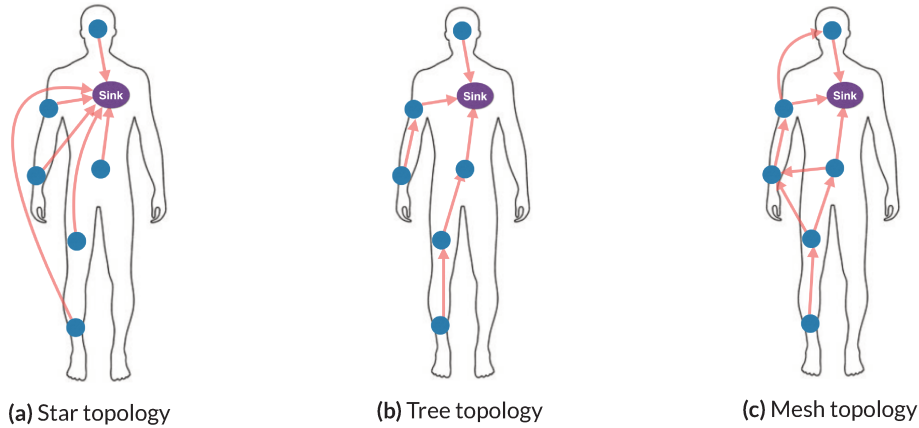


Figure 2.5: WBAN topologies

An in-body network is a set of implanted or invasive sensors in human body that communicate with an exterior gateway i.e. *Sink*. Human body communications (HBCs) realize wireless

body area networks (WBANs) using the human body as a transmission channel without wired or wireless connections ([100], [132]). As for on-body sensors, the communication quality depends on body postures and Transmitter and receiver position. However, channel characteristics are different. HBC uses the relatively low loss human body as communication medium to connect sensors.

2.7.2 WBAN SPECIFIC CHANNEL MODEL: THE INTEGRATED MOBILITY MODEL TOWARDS COMMUNICATION PROTOCOLS PERFORMANCE EVALUATION

Our work is motivated by the cross domain research between electronics and computer science that creates the premises to realize realistic simulations for WBAN and the recent apparition of realistic channel models. Thus, we integrated the channel model proposed in [89] based on the realistic human postures (figure 2.6) to the OMNeT++ simulator [213] enriched with the Mixim framework [109].

We chose to implement over the physical layer implementation provided by the Mixim framework [109] a realistic channel model published in [89]. This channel model corresponds to the on-body 2.45 GHz channel within a network of 7 nodes, that belong to the same WBAN. Nodes use small directional antennas modeled as if they were 1.5 cm away from the body.

Nodes are assumed to be attached to the human body on the head, chest, upper arm, wrist, navel, thigh, and ankle. Considering the application of vital sensor monitoring for medical and health-care, these nodes are selected based on the possible vital sensors, as shown in table 2.1.

Nodes positions are calculated in 7 postures illustrated on Fig. 2.6: walking (walk), walking weakly (weak), running (run), sitting down (sit), wearing a jacket (wear), sleeping (sleep), and lying down (lie). Walk, weak, and run are variations of walking motions. Sit and lie are variations of up-and-down movement. Wear and sleep are irregular movements. The wear, weak and lie positions are the most stable positions and present few weak links. The run, walk and sit positions usually present links with good quality, with the exception of a few high standard deviation links, such as the ones involving the ankle node, which indicate frequent quality changes. The lie position shows some weak links (ankle node) and some links with high variation (thigh node). Finally, the sleep position presents some very weak links with a limited variation, which means that some nodes may be difficult to contact. These postures were initially modeled in [23] using Poser and determined the channel characteristics using the Finite-Difference Time-Domain method [222]. FDTD is an electromagnetic modeling technique that discretizes the problem space into grids by differential form of time and space.

Channel attenuation is calculated between each couple of nodes for each of these postures and represented as the average channel attenuation (in dB) and its standard deviation (in dBm). Path losses are modeled by normal distributions whose characteristics are reported in Tables

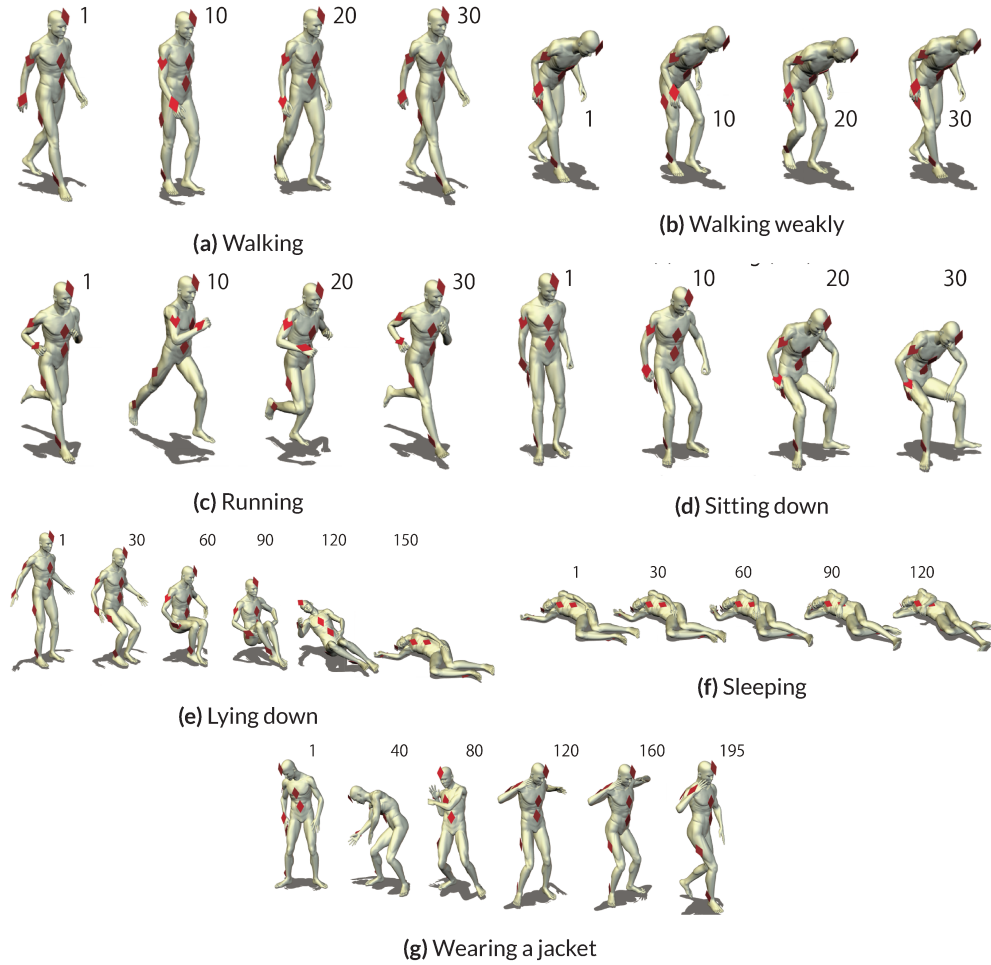


Figure 2.6: Postures used in [89] to model the WBAN channel (Pictures source: [89])

2.4, 2.6 and 2.5 for the walking posture. In this table, the upper triangle reports the mean attenuations between couples of nodes, while the lower triangle reports the corresponding standard deviation. For example, the mean signal attenuation between the couple of nodes (*navel,chest*) is equal to 3.6 db and this attenuation standard deviation is equal to .5 dBm. Small value of mean attenuation means nodes are close to each other while a high value of standard deviation means high movements.

The model takes into account shadowing, reflection, diffraction, and scattering by body parts.

A single-hop communication and preemptive routing are not suitable for WBAN environment. Thus, many works discussed multi-hop on WBAN [218] including Naganawa *et al.* studied in their paper [89] a cooperative transmission scheme: two-hop relaying scheme. Using the

		Mean [dB]						
		navel	chest	head	upper arm	ankle	thigh	wrist
Std. Dev [dB]	navel		30.6	45.1	44.4	57.4	45.8	41.0
	chest	0.5		38.5	40.6	58.2	51.6	45.1
	head	0.8	0.5		45.4	64.0	61.3	49.7
	upper arm	5.8	5.2	5.1		54.2	45.5	34.0
	ankle	4.3	3.4	5.0	3.1		40.6	48.9
	thigh	2.0	2.5	6.8	4.8	1.0		35.0
	wrist	5.0	3.6	3.8	2.5	3.8	3.3	
	(a) Walking posture							
		Mean [dB]						
		navel	chest	head	upper arm	ankle	thigh	wrist
Std. Dev [dB]	navel		31.4	47.4	54.5	57.9	44.8	45.9
	chest	1.4		41.0	39.2	61.0	49.9	41.2
	head	3.5	2.9		41.3	65.6	59.3	45.5
	upper arm	9.9	8.4	8.4		58.0	52.4	33.8
	ankle	6.9	6.9	5.7	8.2		39.0	56.9
	thigh	2.2	4.8	7.3	7.8	1.8		49.6
	wrist	6.1	8.2	3.5	4.6	7.5	11.6	
	(b) Running posture							

Table 2.4: Mean (upper triangle) and standard deviation (lower triangle) of the links path losses for walking and running postures (Source [89])

simulated path loss, the performance of such scheme were evaluated by comparing the outage probability using different relay nodes against a direct link between a source and a destination. They advocate for the use of multi-hops communication, adding to this, a significant decrease of the transmission power. A cooperative transmission scheme improves WBAN mobility.

2.8 CONCLUSION

WBAN has been paid attention in healthcare and medical application field. To achieve a proper WBAN system using miniature devices, a reliable and efficient WBAN communication protocol is required. In addition, a one promising application is a wireless patient monitoring be-

		Mean [dB]						
Std. Dev [dB]		navel	chest	head	upper arm	ankle	thigh	wrist
	navel		31.7	64.3	66.5	72.5	56.3	58.6
	chest	4.3		50.9	51.9	72.4	51.3	44.1
	head	10.4	10.6		39.0	69.4	59.9	42.5
	upper arm	4.6	2.7	11.3		51.5	42.7	30.9
	ankle	5.7	7.5	9.3	0.8		35.7	56.8
	thigh	5.0	2.1	10.8	2.6	0.9		48.9
	wrist	7.8	4.1	7.2	3.6	2.8	2.5	

(a) Sleeping posture

		Mean [dB]						
Std. Dev [dB]		navel	chest	head	upper arm	ankle	thigh	wrist
	navel		27.4	43.3	56.8	62.8	45.0	52.0
	chest	3.4		37.4	51.4	60.4	47.7	50.9
	head	4.9	3.6		49.2	64.0	51.7	46.8
	upper arm	6.7	5.1	9.2		52.3	52.9	31.1
	ankle	7.1	9.9	8.8	4.1		39.5	55.1
	thigh	2.5	6.3	7.0	5.1	1.7		52.3
	wrist	7.4	5.9	5.9	4.8	10.8	7.7	

(b) Wearing jacket posture

Table 2.5: Mean (upper triangle) and standard deviation (lower triangle) of the links path losses for sleeping and wearing jacket postures (Source [89])

cause the wireless technology makes patient not restricted by constraints on their location and activity.

However, the key issue, is to design protocols that ensure reliability for the critical communicated data and a long lifetime for the miniaturized sensors. Indeed, human body exhibits a high and instantaneous mobility and as a result, WBAN topology changes rapidly because of posture changes and movement that causes data loss. Hence, mobility model plays a vital role on the accuracy of WBAN communication protocol evaluation. A good mobility model is essential for performance evaluation of protocols for wireless networks with node mobility. In the following chapters, for communication protocols evaluation in a WBAN context, we integrated, to Omnet++ simulator, the specific channel and mobility model described in paragraph 2.7.2. In particular, we exploit links characteristics between 7 nodes attached to human body

		Mean [dB]						
Std. Dev [dB]		navel	chest	head	upper arm	ankle	thigh	wrist
	navel		26.1	42.4	44.3	55.4	44.9	34.0
	chest	0.4		38.1	37.3	58.8	47.1	41.7
	head	1.3	0.7		44.5	52.4	60.0	42.8
	upper arm	5.5	5.5	6.8		53.7	45.1	34.5
	ankle	4.2	4.6	3.3	6.1		42.4	49.2
	thigh	2.2	5.3	5.4	4.8	2.2		37.9
	wrist	2.8	2.5	1.5	3.1	4.8	4.4	

(a) Walking weakly posture

		Mean [dB]						
Std. Dev [dB]		navel	chest	head	upper arm	ankle	thigh	wrist
	navel		27.9	41.1	41.5	59.6	48.3	38.6
	chest	1.0		37.0	36.0	60.0	51.0	43.2
	head	1.6	0.8		42.1	63.7	59.1	46.9
	upper arm	5.3	4.8	6.3		63.7	49.0	37.7
	ankle	8.4	8.0	8.7	8.1		40.9	60.2
	thigh	6.3	5.3	7.8	5.5	6.3		35.1
	wrist	4.6	5.3	5.5	5.7	9.6	6.9	

(b) Sitting posture

		Mean [dB]						
Std. Dev [dB]		navel	chest	head	upper arm	ankle	thigh	wrist
	navel		30.5	45.1	54.1	65.0	55.8	49.7
	chest	2.2		38.2	43.4	63.6	54.3	46.5
	head	3.3	1.3		40.0	61.8	58.6	45.5
	upper arm	5.9	4.2	4.2		58.3	50.1	38.8
	ankle	6.9	5.8	7.0	5.1		41.2	44.7
	thigh	12.4	10.1	10.1	10.1	7.2		41.6
	wrist	6.3	4.9	3.8	1.9	9.6	8.8	

(c) Lying posture

Table 2.6: Mean (upper triangle) and standard deviation (lower triangle) of the links path losses for walking weakly, sitting and lying postures (Source [89])

in a scenario of several postures ranging from static to high mobility postures.

3

Converge-cast in Wireless Body Area Networks

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3.1 INTRODUCTION

This chapter focuses on the *converge-cast* problem or data gathering in Wireless Body Area Network (WBAN).

Converge-cast is a many-to-one communication primitive where several sources try to communicate with a predefined destination. In WBAN, such communication is illustrated when sensor nodes transmit their data to a central node, i.e. *Sink* node, directly or through intermediate nodes (figure 3.1). The communication is initiated either by a previous request from *Sink* node, or by a predefined periodic sending of the measured data or by an alert generated following any failure or threshold overtaking. In addition, in a multi-hop network, sources can act as intermediate nodes depending on their position.

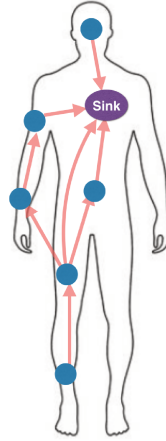


Figure 3.1: Converge-cast principle illustration

Communication is a challenging problem for WBAN due to human postural mobility. Indeed, links quality changes rapidly due to body shadowing and body mobility. Hence, converge-cast issues range from reliable and energy efficient communication to low latency and it is important to understand the different dynamics in WBAN and the tradeoff of different solutions and approaches to ensure converge-cast in WBAN.

Our contribution is multifold:

- First, we analyze the impact of the body's mobility (figure 2.6) on various classes of multi-hop converge-cast strategies. We concentrate only on flat (i.e. non cross-layer) converge-cast strategies. *Eleven* representative converge-cast strategies were classified in

three categories: attenuation-based, gossip-based and multi-path-based strategies, implemented and evaluated through simulations. We integrated the channel model proposed in [89] to the OMNeT++ simulator [213] enriched with the Mixim framework [109].

Our simulations show that converge-cast strategies, inspired from Delay Tolerant Network (DTN) and Wireless Sensor Network (WSN) areas cannot be extrapolated to WBAN without a deeper investigation due to postural body movements and the topological partitioning provoked by important link attenuations.

- Second, we propose a novel converge-cast strategy called *Hybrid*. Our protocol is resorted to different techniques in order to cope with WBAN environment constraints. As a result, our novel strategy manages to find a fair compromise in optimizing the different WBAN communication criterias such as reliability, latency and energy consumption.

This work was published in [31].

The chapter is organized as follow: section 3.2 discusses relevant related works. In section 3.3 we present our original contribution: the classification of converge-cast strategies borrowed from DTN and WSN areas altogether with our novel strategy. Section 3.4 discusses strategies performance evaluation regarding resiliency to human body mobility, end-to-end delay and energy consumption. Section 3.5 concludes the chapter.

3.2 RELATED WORK

In this section we propose an overview of the existing strategies for converge-cast in several areas such as Ad-hoc, DTN, WSN and WBAN.

3.2.1 ROUTING IN MULTI-HOP NETWORKS

Following the classification of protocols coming from ad-hoc networks [35, 197], proactive routing protocols rely on the regular update of a cost function that is based on a network parameter (delay, number of hops, congestion, etc.), on a system-related parameter (battery level, temperature, available memory, etc.), on an application level parameter (measured data) or on a combination of multiple such parameters. On the other hand, reactive routing protocols explore the network when needed, in search for the best path with respect to similar parameters. In both approaches, routes are meant to last during a whole session and repairing broken routes is often costly. Oscillating links, as found in WBANs, may result in a random selection of the links composing paths, depending on the moment when control messages are emitted. The instability will then provoke packets loss and several retransmissions.

WSN protocols seem to be more adapted to links intermittence, nodes turning their radio on and off regularly to save energy. However, most WSN routing protocols [15, 156] either assume that these duty cycles are homogeneous across the network, or that they can be influenced to help routing. In addition, typically, in the literature [45, 95], data is collected from nodes (i.e sources) to the *Sink* node (i.e destination) through a direct spanning tree. However, in WBANs, the disconnections periods are defined by nodes relative to mobility, which is neither perfectly regular, nor identical between each couple of nodes.

In their paper [95], Grover *et al.* focus the issues of SPIN (Sensor Protocol for Information via Negotiation) routing protocols and discuss different versions of SPIN routing protocols. The approach to forward data from a source to a destination is similar to our approach used in *attenuation-based* protocols (section 3.3.1) as it is based on a three-way handshake between the source and its neighbors. Interestingly, via simulations we show that these strategies have interesting performance when stressed in a realistic WBAN context (section 3.4). We are particularly interested in the modified version of SPIN: M-SPIN [168]. In M-SPIN, a node transmits data to the closest node to the *Sink*, the distance is calculated on the basis of hop distance. In our case, the metric is the link's quality between the potential next hop nodes and the *Sink* node. In the context of WBAN, the distance is not an expressive metric for two main reasons: First, the limited number of nodes i.e. a limited number of hops, second, the instantaneous mobility of human body.

Authors of [129] propose an efficient N-To-1 multi-path discovery protocol to find multiple paths from every sensor node to the *Sink* in two route discovery phases, i.e. route update and multi-path extension phases. In the route update phase, a spanning tree is constructed by broadcasting the route update message. At the reception of this message the node set the sender node as parent node. Then in the multi-path extension phase, an alternative path is created by the exchange of messages between the nodes that belong to different branches of the spanning tree. However in the data transmission stage the source node splits its data into multiple packets to be sent over the different paths, which can result in loss of the whole data if a significant packet is lost. In addition the N-to-1 multi-path routing protocol uses the flooding strategy during the route discovery phase, thus leading to a significant consumption of nodes' energy, and additional overhead in the network especially in the context of WBAN networks.

To cope with energy and collision problems, the authors of [217] propose a multi-path routing algorithm that uses two collision-free paths between the source and *Sink* node. The main idea of this protocol is to choose two node-disjoint paths in such a way that the distance between these paths should be greater than the interference range of the sensor nodes. Although their mechanisms help to conserve much more energy compared to [129], it cannot be used in a WBAN context for two reasons: the postural mobility and impossibility to construct two collision free paths.

In [45], authors present CTP – Collection Tree Protocol. The basic idea is to build one or more collection trees all of them rooted at the *Sink*. Each node sends its own data and also forwards data for other nodes. A metric is used to indicate link quality between a node and its parent based on successful delivery ratio of routing messages (beacons) and data messages. However, these protocols have not been tested face to real mobility pattern for WBAN. For this reason, Bu *et al.* [37] show that popular strategies such as CTP [45] (and ORW [70]) perform worse in all the considered mobility patterns of a WBAN channel model.

On the other hand, based on the size of the network (hundreds of nodes) in WSN, the simple monitoring applications and the static network alleviated from mobility constraint, some proposed protocols [228] introduce mechanisms to ensure reliability that are heavy and complex to be adapted to WBAN context.

WBAN could therefore be closer to some types of DTN which are designed to handle connections and disconnection periods. Links intermittent behavior is assumed and handled by having nodes work in store-and-forward mode, i.e, buffering packets until a desired link appears. Several papers (e.g. [92, 137]) propose and evaluate mobility-aware shortest path algorithms in DTN. Even though they address unicast routing, these contributions confirm that efficiency increases with the knowledge of the mobility pattern. In other words, knowing how nodes move allows to reduce the number of unnecessary transmissions and the delivery delay.

Based on the amount of knowledge that is available, algorithms in DTN are, in general, divided into [97]: Dissemination (gossip-based algorithms) and forwarding (overlay-based algorithms).

Gossip consists in disseminating every message to every node or to a subset of nodes in the neighborhood. This approach is adopted when no knowledge about the network is available. The extreme form of gossip is flooding where every message is set to every neighbor, hence maximizing the probability that a message is successfully transferred to its destination by replicating multiple copies of the message. While providing near-optimal performance regarding delay, the primary limitation of these protocols is their energy consumption and their overhead due to excessive packet transmissions. In our context, we investigate the efficiency of various versions of flooding, referred in the sequel as *Gossip-based* algorithms (presented in section 3.3.2).

The overlay-based algorithms use generally tree-based overlays (constructed either on-the-fly or pre-constructed) in order to push the data from the source to *Sink* node. The more precisely the more mobility pattern is characterized, the more optimized the forward will be. However, acquiring this information has a cost and there is a subtle balance to find between duplicate data packets and control messages. Generally the information is related to the spatiotemporal locality: space-locality refers to information about the node's movements (through GPS for example) in order to know which node has a higher probability to pass near the destination.

For this reason, Vahdat *et al.* [210] propose *epidemic routing*. They consider the non-existence of a fully connected path between the source and the destination. Based on that, the source disseminates information through basic flooding on its neighborhood and when two distant nodes eventually meet, they then exchange only the missing messages in order to forward to the destination. The exchange assumes that both nodes keep in memory the list of all received messages. In [21], authors propose PROPHET – a Probabilistic Protocol using History of Encounters and Transitivity. It is an extension of epidemic routing that develops a probabilistic framework for capturing spatiotemporal locality present in the node mobility pattern within a dynamically partitioned wireless network. In addition of exchanging summary vectors, nodes exchange a delivery vector containing a probabilistic metric that indicates how likely a node is able to deliver the message to the specific destination. In WBAN context, this approach has several limitations due to the fact that sensor nodes have limited memory capacity.

In Interplanetary networks (IPN) [38] that connect satellites orbiting around planets, the orbiting objects have predetermined paths and it is possible to predict connections and disconnections with a good accuracy. Routing protocols in IPNs use this regularity to schedule transmissions. In WBANs, the mobility pattern may be quasi-periodical, but some degree of uncertainty exists and links disappear quickly in case of fast motion, which makes it difficult to make predictions. Besides, the wireless channel is less reliable in WBAN than in space.

In vehicular applications of DTN, buses or cars exchange data whenever they meet. Even if the inter-connection delays and the connectivity periods are less regular than in IPN, most solutions consider that connection periods are much shorter than inter-connection intervals, which results in a relatively short transmission window that needs to be detected and used at its best.

3.2.2 ROUTING IN WBAN

Many routing protocols for WBAN are designed by taking some major objectives under consideration, such as, energy efficiency, quick and reliable data delivery, efficient use of available resources, etc.

In WBAN, a link high path loss variation usually reflects movements that may be quasi-regular, resulting in frequent but predictable link connections and disconnections. Classical routing protocols may choose to use or not such links, but to the best of our knowledge, none of the proposed routing protocols in ad-hoc, WSN or DTN was designed to address specifically links with comparable on and off periods and possible sudden changes.

In [125], authors propose EERS–Energy-Efficient Routing Scheme. EERS includes three functional modules: route selection, link quality estimation and data forwarding modules. The proposed scheme addresses adaptive power control and routing in WBAN. The transmission

power of each sensor node adapts in accordance with the link quality. To do so, in link quality estimation and route selection modules, nodes exchange beacons at different power levels to identify the link status which increases the control overhead. In addition, authors introduce five mechanisms to improve EERS performance such as load balancing mechanism, route repair mechanism, etc, which results in a complex implementation for WBAN nodes. Authors also conclude that using a higher fixed transmission power or an adaptive transmission is the solution to meet a high reliability requirements, a conclusion that we will aim to discuss all along this chapter.

A Priority based Energy Aware (PEA) routing protocol is proposed in [196]. Child nodes choose a parent node connected to *Sink* node based on a cost function that depends upon data priority, residual energy and distance of node. Residual energy facilitates load balancing and distance helps in successful packet delivery to parent node. Priority helps to select a best possible path to forward critical data keeping in view the energy constraint in WBAN thanks to a two-hop communication. Authors consider human body mobility through the distance between child nodes and parent nodes. Child node will select the nearest parent while transmitting. Initially, all nodes broadcast Hello packets containing information about their positions, priority and energy level and aiming to identify child nodes, parents node and *Sink*.

In [134], authors discuss two scenarios of communication: Line of Sight (LoS) and None Line of Sight (NLoS) communication to justify the use of a relay node. Hence, a sensor node sends Request To Send (RTS) packet, if it has data packets to send to *Sink* node. If the RTS packet is recognized within a certain time interval, i.e., the *Sink* node is in Line of Sight with sensor node, then the sensor node sends data packets directly to the *Sink*. Otherwise, the *Sink* node is in NLoS with the sensor node, the sensor node will send a wakeup packet to the relay node. After successfully receiving all the data packets, the *Sink* node will send a Receive Acknowledge (RACK) packet to the sensor node. If the sensor node does not receive the RACK packet, then the above process will be repeated until successful transmission. However, the network model used in this protocol is very simple: a sensor node on the chest, senses the data and sends it to the other node i.e. *Sink* node on the wrist. Furthermore, there is a relay node on the wrist to simplify the communication between the sensor node and the *Sink* node which means additional use of hardware device. In addition, the mobility of human body is weakly presented only for walking and running postures. This selection mechanism does not assure that the selected node will improve the reliability. A similar opportunistic routing mechanism is evaluated in [8] using two different path loss models.

Authors of [161] propose PRPLC, a store-and-forward approach and use a probabilistic proactive routing, defining links costs that are automatically adjusted. It aims to update a vector of (probability) likelihoods that a link will be available in a given time slot using Hello messages. The protocol aims to choose the most probable link to route the packet from avail-

able links to avoid buffering and packets loss. They show through simulation and experiments that taking into account the particular mobility of the body improves transmission delay when compared to a traditional probabilistic algorithm for DTN. However, reliability is not 100% insured (PDR is around 88%).

Quwaider and Biswas [162] propose, DVRPLC, an opportunistic routing scheme able to switch between direct links and multi-hop paths when getting out of line of sight. As in [161], DVRPLC selects the most likely path to the sink using a link cost factor standing for the routing cost of the link in time slot. DVRPLC aims in reducing the end to end cumulative cost comparing to PRPLC which only consider the next hop link level.

The same authors present in [159] an adaptation of their algorithm taking into account location-aware networks. Authors start by characterizing the topology and observing the impacts of postural mobility on network partitioning. To do so, each node maintains a neighbor table based on a periodical exchange of hello packets. Then, a stored list of nodes that are known to be closer (physically) to the *Sink* node is pre-programed and a node forwards packets to the first connected node from this list. In case, no connected node is closer to the *Sink* than the node itself, then the node continues buffering the packet till its connectivity status changes. However, authors didn't consider MAC collisions since they were using a polling mechanism managed by *Sink* node that its transmission power is set to a higher value in order to ensure that every node receives the polling. Thus, a node forwards packets (data and hello) only when it is polled by *Sink* node. Also each node sends its neighbor table to the out-of-body server using a full transmission power. Even if authors evaluate the delay, the latter stills important regarding WBAN context.

Guo *et al.* propose MEPF–Minimum Energy Packet Forwarding Protocol [78] which implements the Transmission Power Control (TPC) with Automatic Repeat Request (ARR). The sender makes the decisions of adjusting the transmission power and when to retransmit a packet, i.e a lost packet is retransmitted only when the link quality decreases to a certain threshold. To obtain information about link quality, a machine learning algorithm is designed based on the RSSI values linked to the acknowledgements. They analyze the tradeoff of energy consumption between transmission power and packet retransmission. Retransmission of lost packet increases the throughput, however, authors didn't consider performance metrics such as delay.

Yousaf *et al.* propose in [223] Co-CEStat a cooperative routing protocol. For each sensed data, nodes compare this information to a threshold in order to decide whether the data is critical and has to be sent directly to *Sink* node or it has to be stored until a variation is observed. The idea is to avoid transmissions of the same information. In addition, two types of nodes are defined: normal nodes that only send their own sensed data and advanced nodes with more initial energy that are cooperative nodes. However, authors didn't consider the mobility of the

human-body: during the transmissions of a message over the path already computed, disconnections can happen causing failures. Also, authors didn't consider the protocol performance regarding the end to end delay. Data aggregation could be interesting for specific application but overall data in WBAN are considered critical and has to be delivered to or from *Sink* node in the brief delay ($< 125ms$).

Many other WBAN proposals, such as EDSR [145], do not take into account the mobility of the human-body. EDSR is an on-demand routing protocol that builds routes by flooding Route Request packets if a sender wishes to send data to a destination with no known route. During the transmissions of the message over the path already computed, disconnections can happen causing failures.

In [200], authors propose DARE: Distance Aware Relaying Energy efficient protocol for heterogeneous networks to monitor patients in multi-hop Body Area Sensor Networks (BASNs). The presented protocol is evaluated in a scenario of a ward of a hospital containing eight patients. Different topologies are evaluated by putting the *Sink* node at different locations in the ward. Seven continuously data monitoring sensors or event driven data (Threshold) monitoring sensor are attached to each patient in addition of one Body Relay (BR) placed on the chest. The Body Relay have greater energy resources, compared to the Body Sensors, to relay data to the *Sink* node. Authors evaluate DARE in five scenarios where they vary *Sink* node emplacement in the hospital ward. However, in addition of having a cost with the body relay, also in some scenarios, authors define four sinks instead of one and a Main Sensor (MS) for each patient in order to help the BR to consume less energy. This additional hardwares are not affordable. Also, Packet Delivery Ratio (PDR) remains low for some scenarios and DARE presents a high propagation delay.

Ben Hamida *et al.* propose in [82] OMAR – Opportunistic and Mobility Aware Routing protocol. Authors consider both star and multi-path topologies. At the MAC layer, nodes implement the IEEE 802.15.4 beacon-enabled Medium Access Control (MAC) protocol. Hence, the coordinator broadcasts periodically a beacon to keep all nodes synchronized with the start of MAC super frames. Also nodes broadcast periodically a hello packet which aims to maintain a local neighbor table which contains the list of available links and reflects the instantaneous network connectivity. To take into account mobility, authors, first, classify links into long-term reliable links, short-term reliable or time-varying links and unreliable links. Then, the resulting topology and links characteristics are used for the routing process. Authors considered only two postures: walking and running. In addition, delay wasn't evaluated and PDR is considered as stable.

In [90], authors present AMR and I-AMR protocols. AMR is an adaptive network discovery and routing tree construction protocol for BANs that take into account several metrics (number of hops, RSSI and battery level are combined using fuzzy logic) in selecting the routing

path to *Sink* node. Authors show that taking into account overall metrics improves protocol performance than using a unique metric. With I-AMR, authors improve the time complexity of AMR, especially for a big number of nodes, by modifying the spanning tree construction algorithm.

In [189], authors propose ESR that is based on on-demand routing scheme. A path routing selection is processed based on two functions: energy cost function and path stability function. Even if authors assume mobility they did choose a simple mobility model: the Random Waypoint model. In addition, path discovery process generates a lot of traffic that can not be neglected.

In [55], authors proposed a solution to minimize energy consumption. They deploy some non-sensing, dedicated nodes with additional energy source. This technique minimizes energy consumption of WBAN nodes and enhances the network lifetime. However, additional hardware required for relay nodes increase the cost of the network.

Elias *et al.* propose EAWD–Energy-Aware WBAN Design [59]. EAWD deals with topology constraints by introducing relay nodes number and in order to reduce the total energy consumption as well as the total network installation cost of sensor nodes. Unfortunately, EAWD shows heavy and complex due to many assumptions and omitted considerations. Authors considered the energy consumption and the total costs of mesh network formed by sensors and relay nodes without considering the overhead due to mac, routing and physical clear channel assessment problem.

In [10], a multi-hop routing protocol for WBAN has been proposed. Fixed nodes can be used in the form of relay nodes. To select the forwarder node, a cost function is used dependent on the transmission power of the node, the transceiver’s velocity power vector and the residual energy. Simulation results show that with this protocol network lifetime and PDR are increased.

In [176], Balanced Energy Consumption (BEC) is proposed. The cost function is calculated by considering the distance of the node from the *Sink*. The selection of the forwarder node is performed for a separate round to distribute the load uniformly.

In [135], authors propose an adaptive routing protocol. In this protocol, the core channel information can be used to select the best strategy to select and forward data while reducing energy for each bit sent. Source node will use a relay node only if link’s quality is below a threshold otherwise a direct send to *Sink* node is processed.

A different research direction on the converge-cast topic in WBAN is the cross-layer converge-cast on top of tree-based overlays [115, 227, 36, 41]. In the current work we focus only the flat strategies, a future research direction will be to improve our new proposed strategy (section 3.3) via cross-layer mechanisms and compare its performance with existing cross-layer strategies stressed with a realistic WBAN channel model.

3.2.3 DISCUSSIONS

In the literature, many works assumed a star topology and single hop communication for WBAN. However, it was concluded that a multi-hop communication is more reliable [150, 149] and is required to guarantee low transmission power, low energy wave and efficient data routing by distributing the traffic load over the entire network. In [170], authors characterize the path loss for different parts of human body (arm, back, torso and leg) obtained by measurements on actual humans. They showed that single hop communication is difficult in term of energy consumption and multi-hop communication could be a better choice. In addition, for one-hop topology, congestion may occur at *Sink* node as all sensor nodes are sending to the latter which leads to performance degradation and a low packet reception ratio.

Cooperative routing is a promising technique which exploits the broadcast nature of wireless medium to enhance network performance. There are several works on routing protocols in WBAN exploiting cooperative routing. However, since paths are already computed, these proposals are not resilient to the human body mobility. Indeed, WBAN proposals, such as EDSR [145] or Co-CEStat [223], do not take into account the instantaneous mobility of the human-body: during message transmission over the path already computed, disconnections can happen causing failures. In addition, most of the protocols tries to satisfy a specific requirement and not all QoS requirements (energy efficiency, throughput, delay, etc).

EFFICIENT ROUTING FACTORS & CRITERIA

Routing protocols play an important role in WBAN to improve the performance of the network in terms of delay, coverage, network lifetime and sensors energy consumption.

Below are the parameters to be considered when designing new routing protocols:

End-to-end delay Refers to the time taken for a packet to reach its destination and defines routing algorithm respect to application specificity (example: short delay).

Mobility Routing algorithm should handle topology flexibility face to the instantaneous body mobility.

Forwarding mechanism Defines how packets are routed from one or more sources to one or more destinations.

Discarding mechanism Defines which packets are eligible to forward or not (example: a TTL value equal to 1 leads to packet's discarding).

Data rate Depending on the application, nodes can exchange periodically messages or occasionally with a certain data rate.

3.3 CONVERGE-CAST STRATEGIES CLASSIFICATION

This section describes in details the different converge-cast strategies inspired from DTN and WSN networks. In WBANs, the on and off periods are usually comparable for each link. In most scenarios, except static ones, movements are relatively regular and connections and disconnections periods are of comparable lengths. Even if we can take inspiration from DTN and their store-and-forward philosophy, there is no strong need to influence packets scheduling to make the most of infrequent and short relevant transmission opportunities.

Accordingly, the existing routing protocols proposed in the literature cannot be used directly in WBAN and new challenges and adaptations should be addressed in the design of multi-hop protocols in WBAN.

We propose a classification of several strategies in three different categories: *attenuation-based*, *gossip-based* and *multi-path-based* strategies.

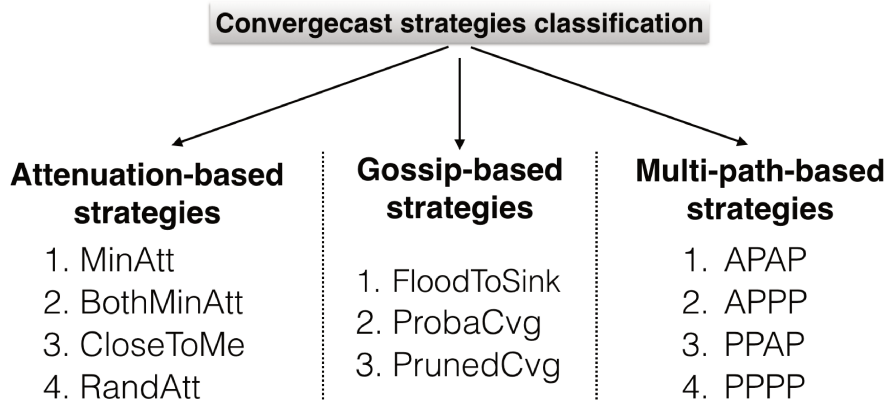


Figure 3.2: Converge-cast strategies classification

Simulation results are presented in section 3.4.

3.3.1 ATTENUATION-BASED STRATEGIES

In the WBAN context, we investigate variants of negotiation protocols, referred as *attenuation-based* algorithms.

In this category, nodes need a specific information in order to take the decision to either forward a message or to hold it. Moreover, nodes have to decide to which neighbor they will forward. According to the mobility model described in section 2.7.2, we will use, as information, the path loss value (*attenuation*) on links between each couple of nodes (similar to the way the classical geographical routing uses the distance to the *Sink*).

The common pattern followed by these strategies is described in figure 3.3.

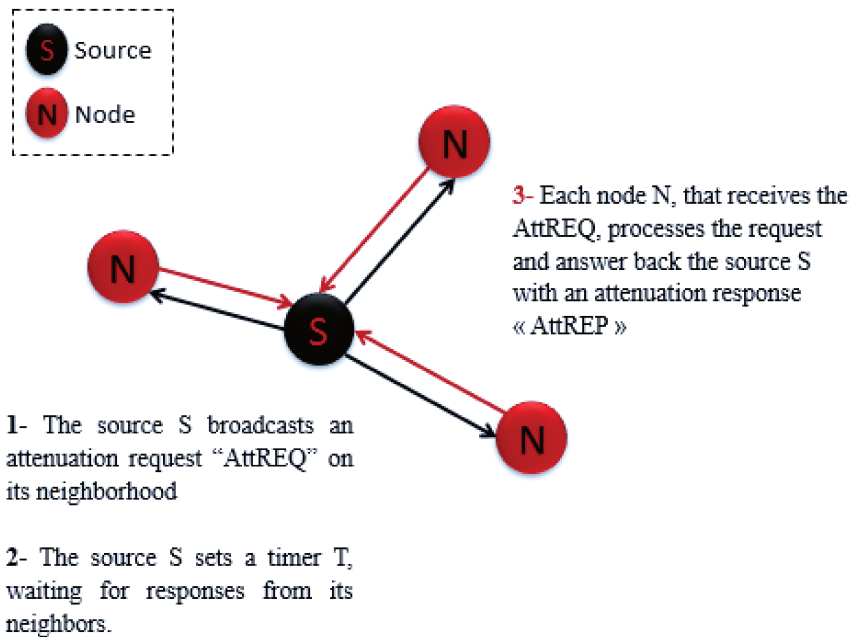


Figure 3.3: Exchanges between a source and its neighbors for attenuation-based strategies

The source S starts by broadcasting a request “AttREQ” asking its neighbors the attenuation value of their link with *Sink* node and sets a timer T . After timer T expiration, S checks the received responses:

- If no response, S rebroadcasts an attenuation request “AttREQ” and activates the timer T again.
- If at least one response is received, S processes the responses, thus we have three strategies:
 1. **MinAtt:** S selects the node such that its response value corresponds to the smallest link attenuation to the *Sink*. In other words, S forwards the message to the node with the most reliable link with the *Sink*.
 2. **BothMinAtt:** S chooses two nodes. They correspond to the closest nodes to the *Sink* based on attenuations values. In case of a unique response, node processes forwarding any way.
 3. **CloseToMe:** In addition of asking link attenuation between each node and the *Sink*, S also requests the attenuation value of the link between it and each node receiving the request. The source S chooses the closest node to itself.

4. **RandAtt:** The source S chooses the next hop based on a random choice between all nodes that answered its request.
- Finally, the node designated to forward the source data message, will follow the same process to designate the next hop.

Timer in attenuation-based strategies is evaluated in section 3.4.1.

3.3.2 GOSSIP-BASED STRATEGIES

In this category, nodes conduct a blind broadcast of messages in the network without relaying on any specific information. These strategies are inspired from the state of the art in WSN and DTN and our recent work related to broadcast in wireless body area networks [28]. Three main strategies are evaluated:

1. **FloodToSink:** Each node, except the *Sink*, rebroadcasts every received message while its *TTL* (Time to Live) is greater than one.
2. **ProbaCvg:** Nodes take the decision to broadcast the message or not depending on a probability $P > 0$. For each node, P is set initially to 1. When receiving a message, each node, except the *Sink*, chooses a random variable r and compares its value with P , if this value is lower than P , then the node broadcasts the message, otherwise it discards it. In case the node broadcasts the message, it divides P by 2. (A P for each node and P varies depending on the number of times the node performed a broadcast).
3. **PrunedCvg:** When receiving a message, nodes, except the *Sink*, choose randomly the next hop to which they forward the message.

3.3.3 MULTI-PATH STRATEGIES

In this category, we exploit predetermined paths (referring to nodes positions on human body) between the source and the *Sink*.

Contrary to the first category (attenuation-based strategies), here the choice is fixed along the simulation. A tree-based routing with a pre-set tree based on nodes position.

In this class nodes have up to two pre-selected privileged neighbors (call in the sequel parents) as shown in Figure 3.4.

The choice of the first path is based on the shortest path to the *Sink* in terms of number of hops, while the second path is chosen in such a way that a node will always have at least one path to the *Sink* even in the case of mobility. If we take the thigh, wrist, and navel nodes as an example, even if the communication between the thigh and wrist nodes is interrupted in case

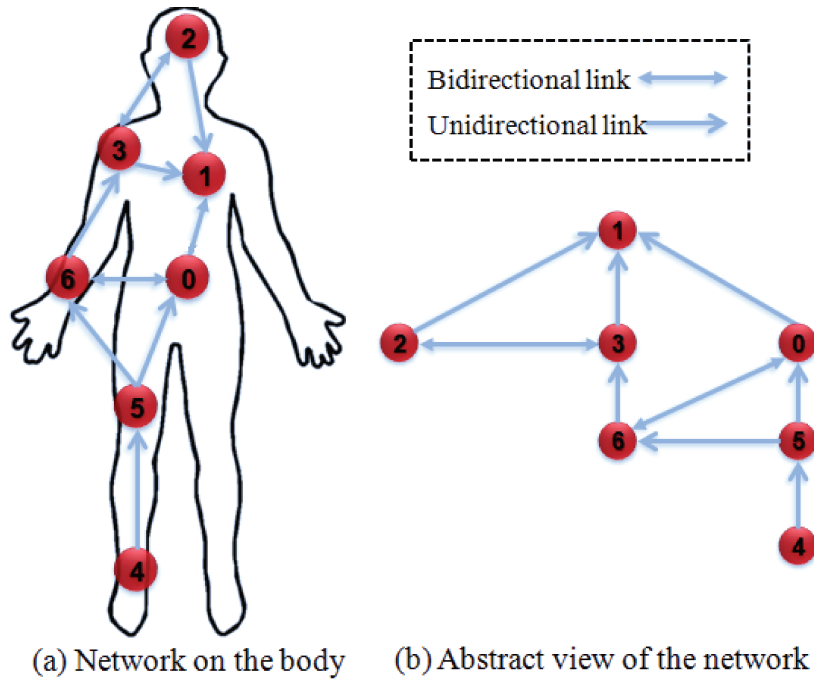


Figure 3.4: Network architecture based on nodes position for multi-path-based strategies

of mobility (wear posture), the distance between the thigh and navel nodes remains the same (it may even decrease if the person leans).

On top of the overlay defined above we execute three strategies presented below:

1. **APAP-All Parents to All Parents:** All nodes send each received message to all pre-defined parents or just to the *Sink* if it is the parent.
2. **APPP-All Parents to Probabilistic Parent:** The source node starts by sending its data to all its pre-defined parent nodes. Each intermediate node will select randomly one of its pre-defined parent nodes. A random variable r is compared to a probability P to take this decision. Note that the probability P influences only the choice of parent not the decision of sending the data or not. P is set to 0.5 which means parents have equal chance to be selected.
3. **PPAP (Probabilistic Parent to All Parents):** The source node sends its data to one of its parent nodes chosen randomly with probability $P > 0$ (set to 0.5 in our simulations). At the reception of the data, the parent nodes verify the existence of the *sink* in their neighbors table. If it exists, they send the data directly to the *sink*, otherwise to all their parents defined in the table.

4. **PPPP-Probabilistic Parent to Probabilistic Parent:** All nodes (source and intermediate nodes) send every message to one of its pre-defined parent nodes chosen randomly as mentioned before (remember: parents have equal chance to be selected). Thus messages follow only one path among the two predefined paths.

3.3.4 OBSERVATIONS

The extended simulations we performed (see Section 3.4.2) and the careful analysis of the above presented strategies conducted us to the following observations that further helped us in designing our novel strategy *Hybrid* (section 3.3.5).

Attenuation-based strategies are based on the channel model. Indeed, each source requests its neighbors about the quality of their links with *Sink* node (this information is assumed to be acquired by nodes). Responses guide source nodes to choose the next hop. So, communication between nodes is based on control message exchanges which has been investigated in other networks than WBAN. However, results show that control packets exchange have a negative influence on latency. Indeed, packets take more time to reach the destination because nodes do not forward immediately.

For *gossip-based* strategies, nodes are able to broadcast often enough since they have fewer restrictions on messages' forwarding. However, a huge number of message copies provokes collisions and high energy consumption.

For *multi-path-based* strategies, nodes exploit all existing paths, for some postures, these strategies achieve high energy consumption.

These observations are supported by simulation results in section 3.4.

3.3.5 NEW CONVERGE-CAST STRATEGY: HYBRID

Our novel strategy *Hybrid* takes advantage of *attenuation-based*, *gossip-based* and *multi-path-based* strategies. Indeed, it behaves as a *multi-path* strategy when messages are forwarded following predetermined paths to parent nodes. However, in order to cope with postural mobility, our novel strategy will introduce messages broadcast, simple flooding as in *gossip-based* strategies. To do so, nodes will first check links status with their parents before sending any data message by broadcasting control messages as for *attenuation-based* strategies.

Hybrid works as follow: when a node has a message to the *Sink* at t :

- It delays the message sending until $t+T$, and tries to reach its parents by sending a *PING* message.
- Only parents and the *Sink*, if they are in node's range, can reply to *PING* message.

- If the node receives at least a reply then it immediately sends its message to its parents.
- If after timer T expiration, the node did not receive any reply, then it broadcasts its data message.

Hybrid implements the following primitives:

- $\text{Deliver}(m\langle\text{SeqNum},\text{SrcAddr},\text{DestAddr}\rangle)$: Sink node delivers m to the application upon receiving m for the first time.
- $\text{Send}(m\langle\text{SeqNum},\text{SrcAddr},\text{DestAddr}\rangle)$: Source node sends m (a unicast sending) to parent nodes.
- $\text{Broadcast}(m\langle\text{SeqNum},\text{SrcAddr},\text{DestAddr}\rangle)$: Source node broadcasts m in the network.

The message m parameters are initially set by the source node.

Broadcast alternative allows peripheral node to join center nodes. This alternative is very useful in constrained posture.

Note that based on multi-path-based strategies, each node knows in advance its parents (pre-set in simulation).

In the following we present *Hybrid* strategy algorithm 1.

CORRECTNESS PROOF OF HYBRID PROTOCOL

In the following we consider that the WBAN network is modeled by a connected graph $G = (V, E)$ where V is the set of nodes in the system and E is the set of communication links (edges between nodes in V). We consider a connected graph. That is, it exists a path between every pair of nodes. In simulations, we carefully choose nodes transmission power to respect this characteristic. Note that if the graph is not connected, there is no coverage. In the following we consider that the communication links are reliable (i.e. no packets loss or collisions).

The Hybrid protocol aims at solving the converge-cast problem that we formalize inspired by the definition proposed in [63].

Definition 1 (Converge-cast). *Let $G = (V, E)$ be the communication graph modeling a network and Sink be the final destination node. A protocol solves the converge-cast problem if the following properties are satisfied.*

- *No creation: No message is delivered at the Sink node application level unless it was sent by a node i such that $i \in V$.*

Algorithm 1 Hybrid strategy algorithm: take a forwarding decision when a packet from application/MAC layer is available to forward

```
1: procedure UPON RECEIVING AN APPLICATION MESSAGE( $m$ )
2:   Set  $SeqNum$  for  $m$ 
3:   Insert  $m\langle SeqNum, SrcAddr, DestAddr\rangle$  in buffer
4:   Start timer  $T$ 
5:   Send(PING message to parent nodes)
6: end procedure
7: procedure UPON RECEIVING A MAC MESSAGE( $m\langle SeqNum, SrcAddr, DestAddr\rangle$ )
8:   if message is a PING then
9:     if DestAddress = MyNetwAddress then
10:      Send(PONG message)           ▷ reply with a PONG to PING's  $SrcAddr$ 
11:    else
12:      Discard PING message
13:    end if
14:  end if
15:  if message is PONG then           ▷ a reply from a parent node
16:    if DestAddress = MyNetwAddress then
17:      Send(buffered DATA message to parents)
18:    else
19:      Discard PONG message
20:    end if
21:  end if
22:  if message is DATA then
23:    if MyNetwAddress = Sink then
24:      if new  $m\langle SeqNum, SrcAddr\rangle$  then
25:        Deliver( $m$ )
26:      else
27:        Discard  $m$ 
28:      end if
29:    else
30:      if (DestAddress = MyNetwAddress) || (DestAddress = BroadcastAddress) then
31:        Send( $m$ ) to all parents
32:      else
33:        Discard  $m$ 
34:      end if
35:    end if
36:  end if
37: end procedure
38: procedure UPON RECEIVING A SELF-MESSAGE, I.E A TIMER( $T$ )   ▷ a message indicating
    timer  $T$  expiration
39:   Set DestAddr with broadcast address
40:   Broadcast( $m$ )           69
41: end procedure
```

- *No duplication: No message is delivered at the Sink node application level more than once.*
- *Reliable Delivery: There is a positive integer $k > 0$ such that a message m sent by any node i ($i \in V$) at time t , is delivered at Sink node at time $t < t' < t + k$.*

NOTATIONS AND DEFINITIONS In the section we introduce the notations and definitions used in our correctness proof.

Definition 2 (eccentricity). *The eccentricity $\epsilon(v)$ of a graph vertex v in a connected graph $G = (V, E)$ is the maximum graph distance between v and any other vertex u of G .*

In this work we are interested in the eccentricity of the Sink node $\epsilon(\text{Sink})$.

Assumption 1. *In the following proofs we consider that TTL is greater than the eccentricity of the $\epsilon(\text{Sink})$.*

Lemma 1. *If a node i broadcasts a message m then nodes in $N(i)$ eventually receive m .*

Proof. Suppose i broadcasted the message m . Assume $\exists j \in N(i)$ such that j didn't receive m . This assumption is false since we assume that links are reliable (no lost messages). \square

Lemma 2 (no duplication). *If Sink node receives a message m then m is delivered at the application level only once.*

Proof. When Sink node receives the message m for the first time then Sink node delivers m (algorithm 1 lines 24 – 25). When the message is a duplicate of an already received message then Sink node discards m (algorithm 1 line 27). \square

Lemma 3 (no creation). *If Sink node receives a message m then m has been sent by the node i such that $i \in V$.*

Proof. Assume Sink node receives a message m that has not been sent by i such that $i \in V$. This means that the message has been created by another node j such that $j \notin V$ or there was a steal message in the channels. The first assumption contradicts the algorithm since no node (except $i \in V$) creates a new message. The second assumption contradicts the hypothesis that the links are reliable. \square

In the following we consider that links are reliable and the communication delays between two neighboring nodes are bounded.

Lemma 4 (Reliable Delivery). *There is a positive integer $k > 0$ such that a message m sent by any node i ($i \in V$) at time t , is delivered at Sink node at time $t < t' < t + k$.*

Proof. Let i be a node in the network.

Let t_1 such that $i \in V$ has an application message m to send to *Sink* node then i broadcasts a PING message to parent nodes in the neighborhood (line 5) and arms a timer T (line 4).

At t_1 the distance between the message m and the Sink is at most equal to $\epsilon(\text{Sink})$.

Let t_2 be the time such that either parents of node i respond with a PONG message to i (line 16) or timer T expires (line 38).

In the first case i sends m to its parents ($N(i)$, see line 17). In the second case i broadcasts m (lines 39 – 40).

From the hypothesis on the communication links, $\exists k_1 > 0$, such that $t_1 < t_2 < t_1 + k_1$.

Since the communication links are reliable and the communication delays are assumed bounded, there is a $k_2 > 0$ such that by time $t_2 < t_3 < t_2 + k_2$, all nodes in $N(i)$ receive m and forward m to their parents (lines 30 – 31). It follows that the distance between the message m and the *Sink* node is decreased by at least 1.

The above process is repeated recursively until the message arrives at some node $j \in N_{\epsilon(\text{Sink})}(i)$ at time $t_{\epsilon(\text{Sink})-1}$.

j sends m to all its parent nodes (including *Sink* node). By the hypothesis there exists $k_{\epsilon(\text{Sink})-1}$ such that *Sink* node receives m by time $t_{\epsilon(\text{Sink})-1} < t_{\epsilon(\text{Sink})} < t_{\epsilon(\text{Sink})-1} + k_{\epsilon(\text{Sink})-1}$.

Let $k = k_1 + k_2 + \dots + k_{\epsilon(\text{Sink})-1}$. It follows that the message m sent at time t by a node i , such that $i \in V$, arrives at *Sink* node by time t' , $t < t' < t + k$. \square

3.4 CONVERGE-CAST STRATEGIES PERFORMANCE ANALYSIS

To compare the different converge-cast strategies described in section 3.3, we evaluate three parameters:

- **Packet Delivery Ratio (PDR):** Each sensor node sends one message with final destination the *Sink* node. We therefore calculate the number of received messages at the *Sink* node level presented as a percentage in the graphs in section 3.4.2. Low percentage means nodes' messages didn't reach their final destination (i.e. they didn't reach *Sink* node).
- **Latency:** The end to end delay is the average time a message takes to reach the final destination (i.e. the *Sink* node).
- **Number of transmissions and receptions:** Because communication is considered as a high energy consumer. This key parameter gives us an estimation of energy consumption.

3.4.1 SIMULATION SETTINGS

We evaluate the different algorithms described in section 3.3 in a realistic WBAN scenario.

We implemented these strategies under the OMNeT++ simulator [4] (section 2.6.3) enriched with the Mixim project [109] (section 2.6.3). On top of the channel model described in 2.7.2, we used the standard protocols implementations provided by the Mixim framework. In particular, we used, for the medium access control layer, IEEE 802.15.4 implementation. The sensitivity levels, packets header length and other basic information and parameters are taken from the IEEE 802.15.4 standard.

Each data point is the average of 50 simulations run with different seeds. We used Omnet++ default internal random number generator, i.e. the Mersenne Twister implementation (cMersenneTwister; MT19937) for the uniform distribution, with different initialization seeds for each run, and the normal distribution generator (cNormal) for the signal attenuation.

Simulations are performed with only one packet transmission from each node to the *Sink* node (the latter is positioned at the chest).

Before comparing algorithms, we need to select general parameters values in order to provide a fair comparison. This includes some protocol-specific parameters described above such as timers value, as well as more general parameters such as the nodes transmission power, or the maximum allowed TTL.

TIME-TO-LIVE (TTL) SETTING

The Time-To-Live (TTL) is a field of the packet. Its value is initialized by the source node and is decreased at each hop. This mechanism limits packets retransmissions. A high TTL value results in a huge number of packets traveling in the network, provoking queueing and collisions, while a low value limits the decision power of the different algorithms. Setting this value in a low diameter mobile network may be uneasy, that's why we rely on simulation results to find a fair value. In our implementation, the TTL is decremented from the first transmission, which means that a packet whose initial TTL value is equal to 1 will only be emitted once and never be forwarded. Simulations are conducted in walk posture with a transmission power equals to $-50dBm$.

Figures 3.5 and 3.6 show the percentage of PDR in function of TTL.

In the first group, *PrunedCvg* and *RandAtt* strategies show the lowest percentage when TTL is equal to 1. Packet is sent only once to a randomly chosen node with a low probability that the latter is the *Sink* node.

We also notice that *FloodToSink* strategy performance decreases while TTL value increases. A high TTL value generates a lot of packets in the network which creates collisions and packets loss. A same behavior for *ProbaCvg* with a less drastic decrease in the PDR with TTL increase.

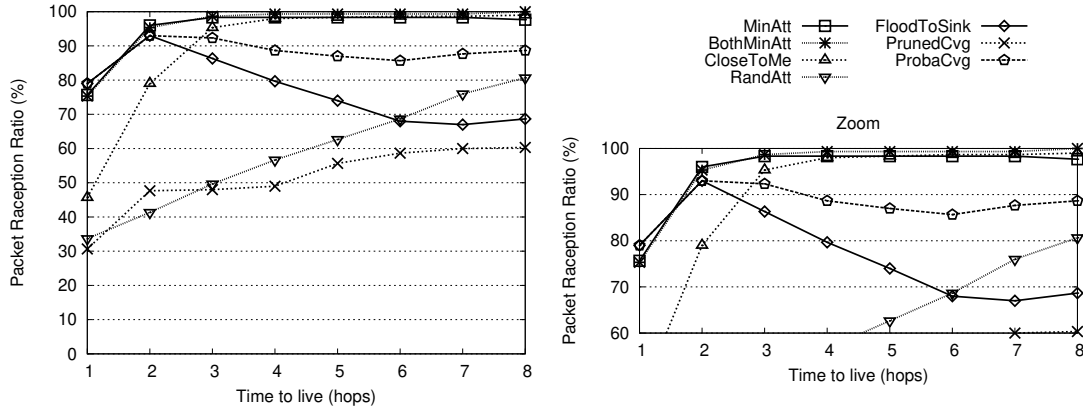


Figure 3.5: Packet delivery ratio in function of TTL (Converge-cast strategies: First group)

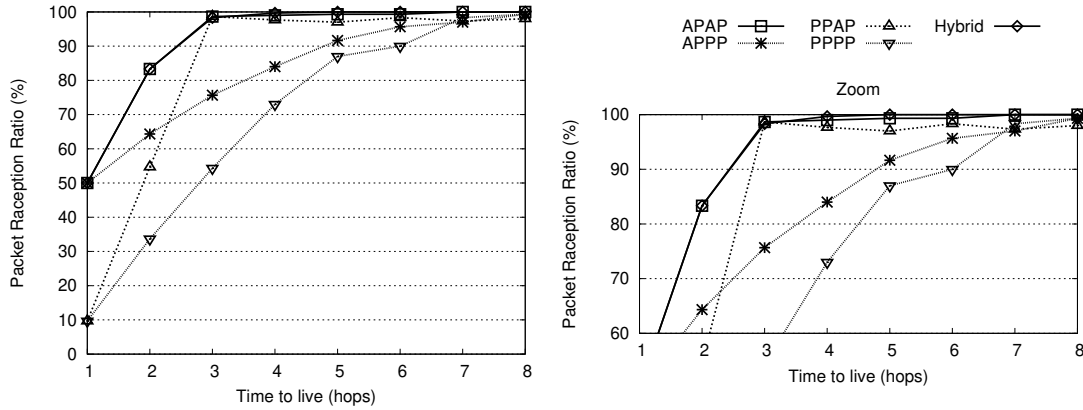


Figure 3.6: Packet delivery ratio in function of TTL (Converge-cast strategies: Second group)

In the second group, *PPAP* and *PPPP* show the lowest PDR. The first transmission targets only one parent node. The latter is able to forward the packet to *Sink* node since *TTL* is equal to 1. However, with $TTL > 1$, *PPAP* outperforms *PPPP*.

Attenuation-based strategies show the best performance with *TTL* equals to 1. Unlike, *Multipath-based* strategies, *Sink* node could be reached from the first transmission attempt if the latter responds to the attenuation request broadcasted by source node.

TTL parameter will be set to 5 in our simulations. Starting from this value, performance of most of the strategies doesn't change.

NODES TRANSMISSION POWER SETTING

We compare the performance of the different strategies in search for the minimum transmission power that allows reasonable communication for a receiver sensitivity of -100 dBm con-

sidering the channel attenuation. We seek for the value of the transmission power that ensures the network is connected over time, while limiting energy consumption and devices temperature. In addition, a comparison with a one hop strategy is conducted.

Figures 3.7 & 3.8 show the percentage of PDR when the transmission power increases from -60 dBm to 0 dBm in walking and sleeping postures. Recall that during simulation the TTL is set to 5.

In sleeping posture, with $-55dBm$, a one-hop transmission reaches reaches 70% while *Hybrid* strategy reaches 95% of successfully received packets.

In single-hop communication, nodes use more energy to reach *Sink* node whereas in multi-hop communication the energy consumption of the forwarding nodes that are closer to the *Sink* node increases. Hence, our investigation to identify the best strategy that ensures the trade-off between reliability and energy consumption.

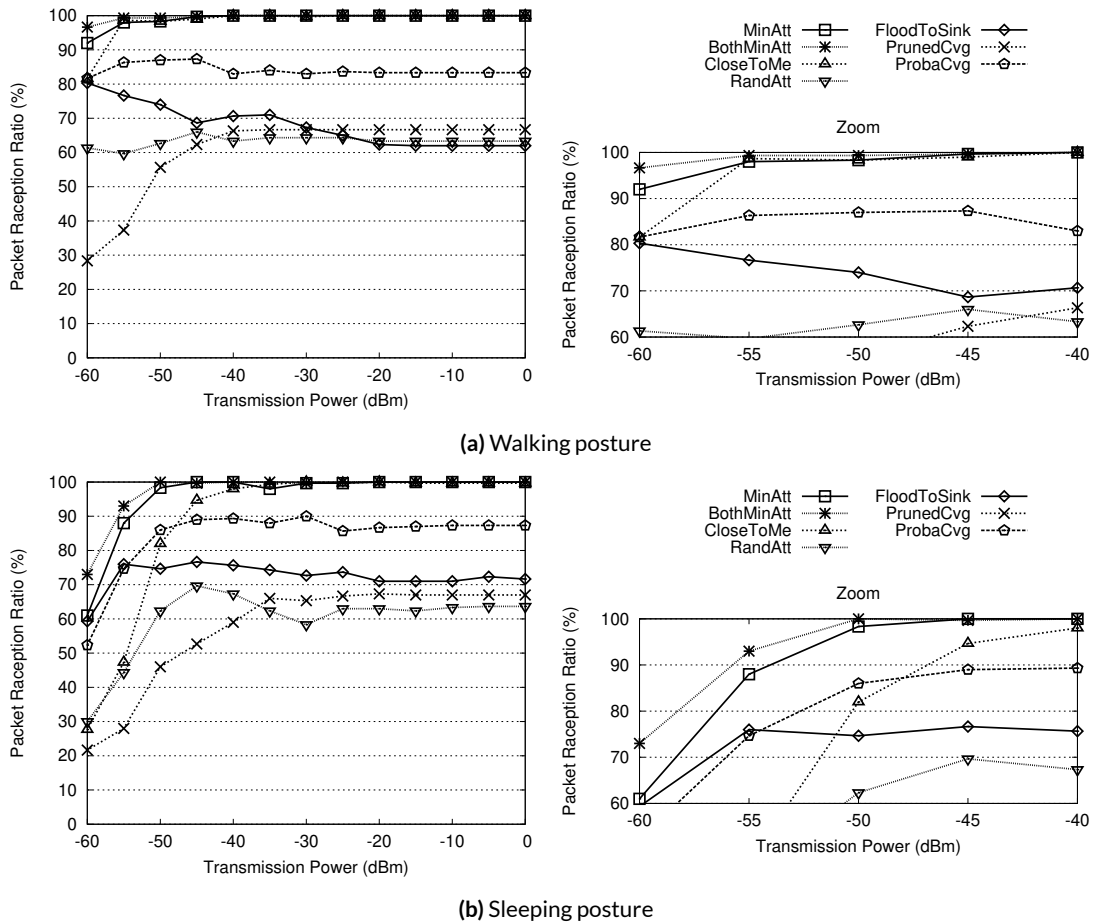


Figure 3.7: Packet delivery ratio in function of nodes transmission power (Converge-cast strategies: First group)

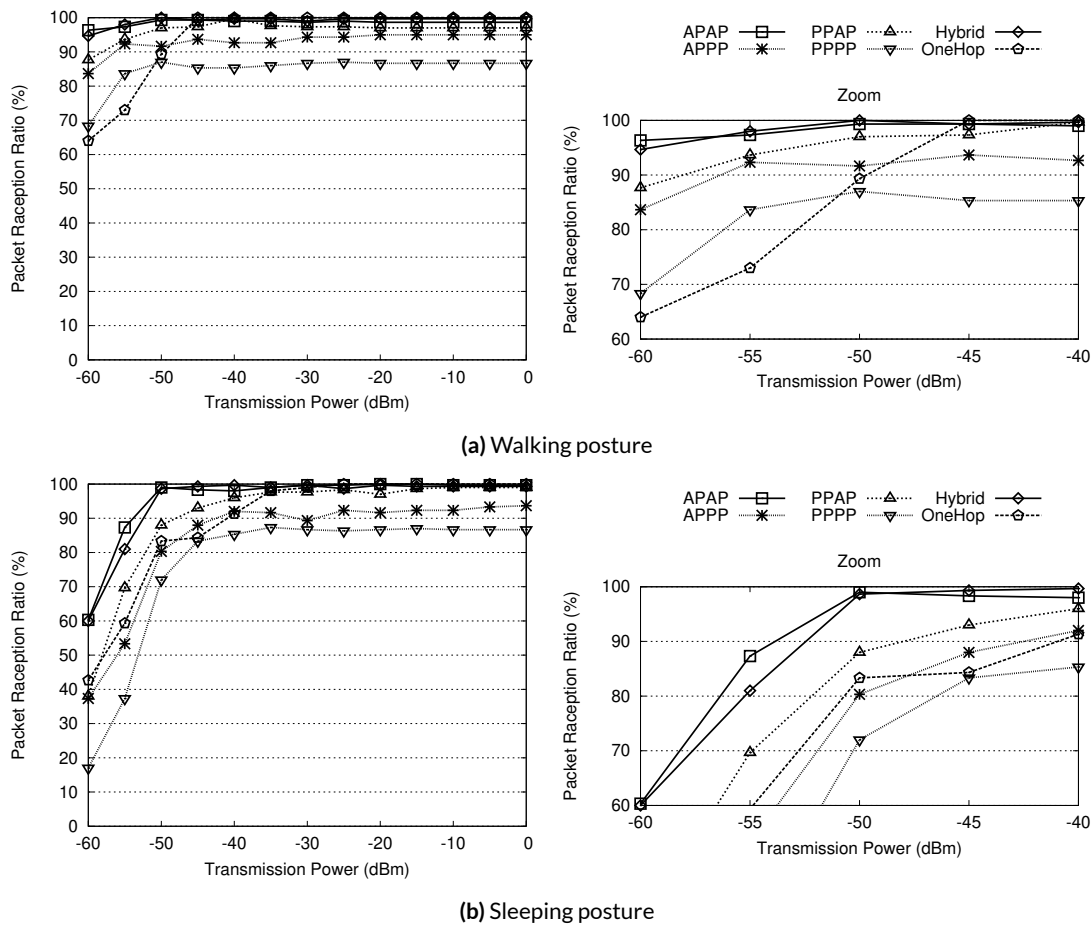


Figure 3.8: Packet delivery ratio in function of nodes transmission power (Converge-cast strategies: Second group)

In the sequel, simulations are conducted with nodes' transmission power equals to -50dBm . Figures show that with this value some strategies like *BothMinAtt* in sleep posture or *Hybrid* in walk posture reach 100% of reliability.

TIMER STUDY FOR CORRESPONDING STRATEGIES

This study targets *Attenuation-based* strategies and *Hybrid* strategy.

When a node has a data message from application layer to forward to *Sink* node, it broadcasts a message of type PING for Hybrid strategy or Attenuation Request for attenuation-based strategies in the neighborhood and starts a timer waiting for responses.

In figure 3.9, we present simulation results of the PDR in function of the timer duration in seconds. Results are shown in walking posture. Recall that TTL is set to 5 and transmission

power is set to $-50dBm$.

RandAtt strategy show a low PDR comparing to the other strategies. Even if at the beginning the percentage shows an increase, it rapidly stagnates around 65%. In the sequel, simulation results will confirm that this strategy is not adapted for WBAN.

For the other strategies, including our new strategy Hybrid, PDR increases with timer value to reach 100% by 200 millisecond.

We chose a timer value equals to 200 milliseconds because it is the first value that allows a full packet delivery ratio (100%). A higher value will induce a higher latency.

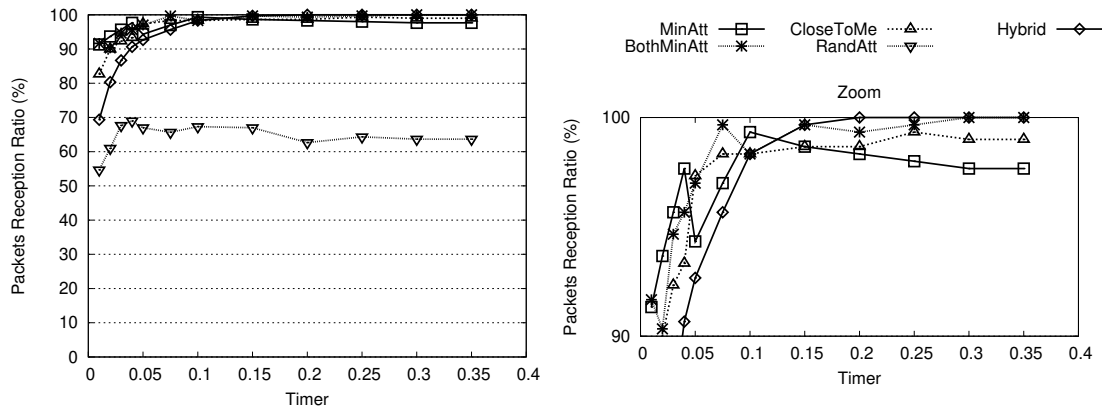


Figure 3.9: Packet delivery ratio for different timer values for Attenuation-based and Hybrid converge-cast protocols

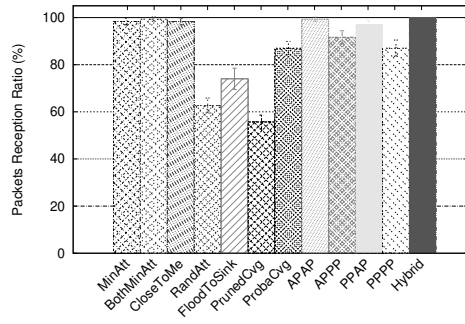
3.4.2 SIMULATION RESULTS

PACKET DELIVERY RATIO (PDR) FOR CONVERGE-CAST STRATEGIES

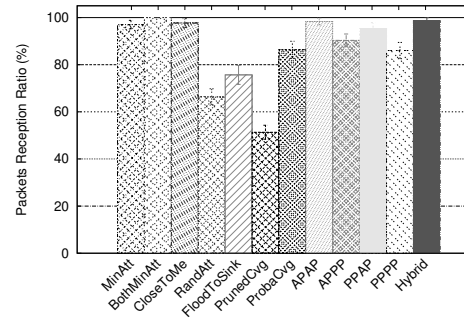
Figure 3.10 details the percentage of PDR for various body postures and highlights the behavior of each strategy face to human body mobility.

Gossip-based strategies present, in almost all postures, the lowest PDR. In this category, there is no condition to stop packets' forward except the *TTL* parameter, which is set to 5 in our simulations. For *ProbaCvg* strategy, forwarding a packet is restricted throughout the simulation because *P* value is divided by 2 after each transmission. As a consequence, the number of packet copies in the network decreases as well as collisions for some postures, which is reflected with a high PDR compared to *FloodToSink* strategy. For *PrunedCvg* strategy, a node forwards the packet to a randomly chosen node. This non-logic choice results in low performance.

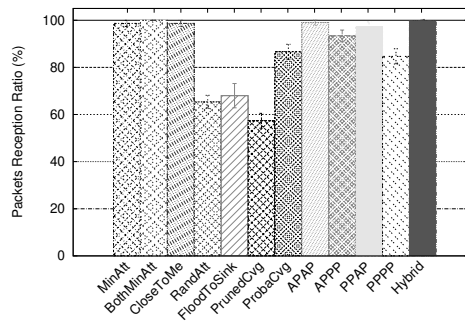
Although each one of the three first *attenuation-based* strategies processes differently attenuation responses, we observe that they show almost similar values. Unlike *MinAtt* and *Close-*



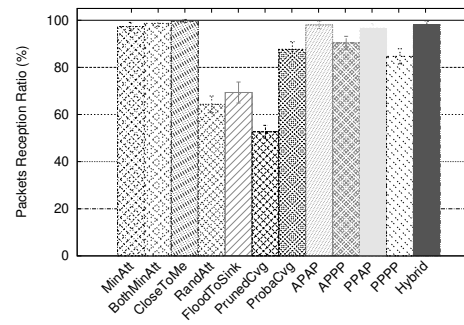
(a) Walking posture



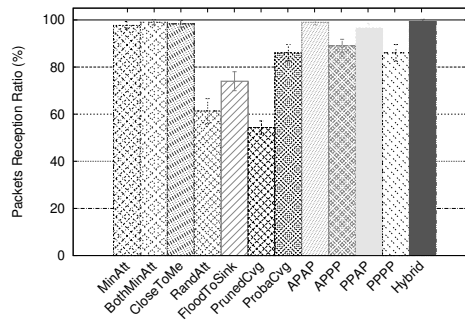
(b) Running posture



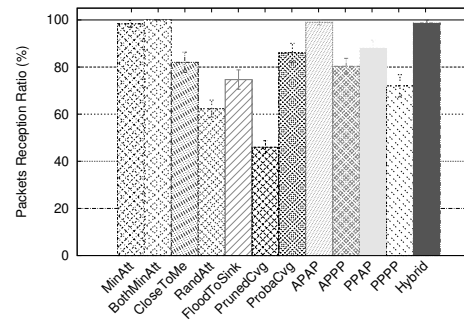
(c) Walking weakly posture



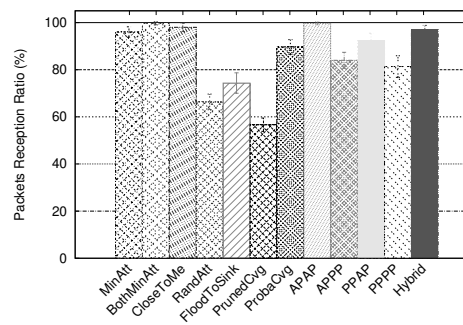
(d) Sitting posture



(e) Lying posture



(f) Sleeping posture



(g) Wearing a jacket posture

Figure 3.10: PDR per posture for all converge-cast strategies

ToMe strategies, in *BothMinAtt* strategy nodes target two neighbors in order to increase converge-cast process probability of success, then, results show that for some postures, *BothMinAtt* strategy has the highest end to end success rate. For *RandAtt* strategy the random choice between all the responses leads to a low PDR.

From figure 3.10, *multi-path-based* strategies present a higher PDR than *gossip-based* strategies and lower than *Attenuation-based* strategies. However, figure 3.10 shows that *APAP* strategy competes with *Attenuation-based* strategies.

APAP outperforms *gossip-based* strategies for all postures. Same for *APPP* strategy except for irregular postures like sleeping or wearing jacket where *ProbaCvg* shows better results. For *multi-path-based* strategies, *PPPP* strategy has the lowest PDR. With this strategy, packets are forwarded along a single path and next hops are chosen randomly. Compared to *APAP* and *APPP* strategies, this shows the importance of multi-path to ensure reliability. It also raises the importance of the first packet's transmission in the network. Indeed, with *APAP* and *APPP*, at the first attempt to send the message, the source chooses both predefined parents while with *PPPP* the source chooses only one parent as next hop.

Our novel strategy *Hybrid* shows a good PDR. For two postures *walking and lying*, it has the highest ratio. For the others postures, it is the closest to the best success rate reflecting a less significant variation depending on wearer posture.

LATENCY FOR CONVERGE-CAST STRATEGIES

Figure 3.11 presents end to end delay per posture. For all strategies, the delay is affected by human body posture with different degree depending on the corresponding protocol functioning.

In *attenuation-based* strategies, a node broadcasts attenuation requests and delays forwarding of data packets until receiving at least one response from neighbors. From figure 3.11, this delay has a significant impact on the end to end delay. Indeed, almost for all postures, these strategies have the highest delay especially *randAtt* strategy due to the probabilistic choice of the next hop.

Comparing *MinAtt* and *BothMinAtt* strategies with *Hybrid* or *APAP*, we notice that the delay is at least three times higher despite a close PDR.

In *multi-path-based* strategies, *APAP* strategy has the lowest end to end delay. With this strategy, source node exploits all the existing paths to reach the *Sink* node contrary to a probabilistic choice in *PPPP* strategy. A randomly chosen parent can be farther from the *Sink* than the initiating node which increases the delay and also the probability of packet loss.

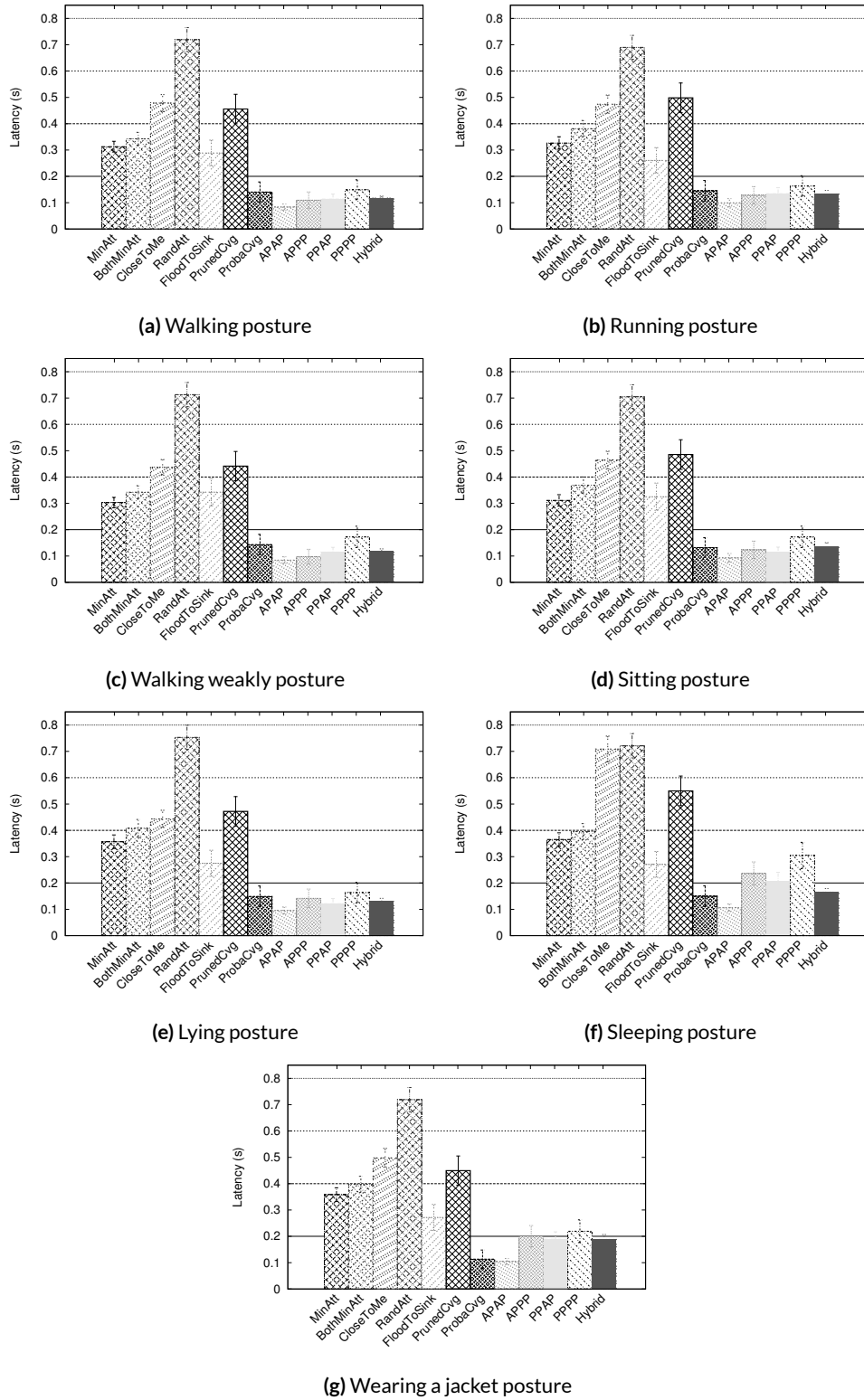


Figure 3.11: Latency per posture for all converge-cast strategies

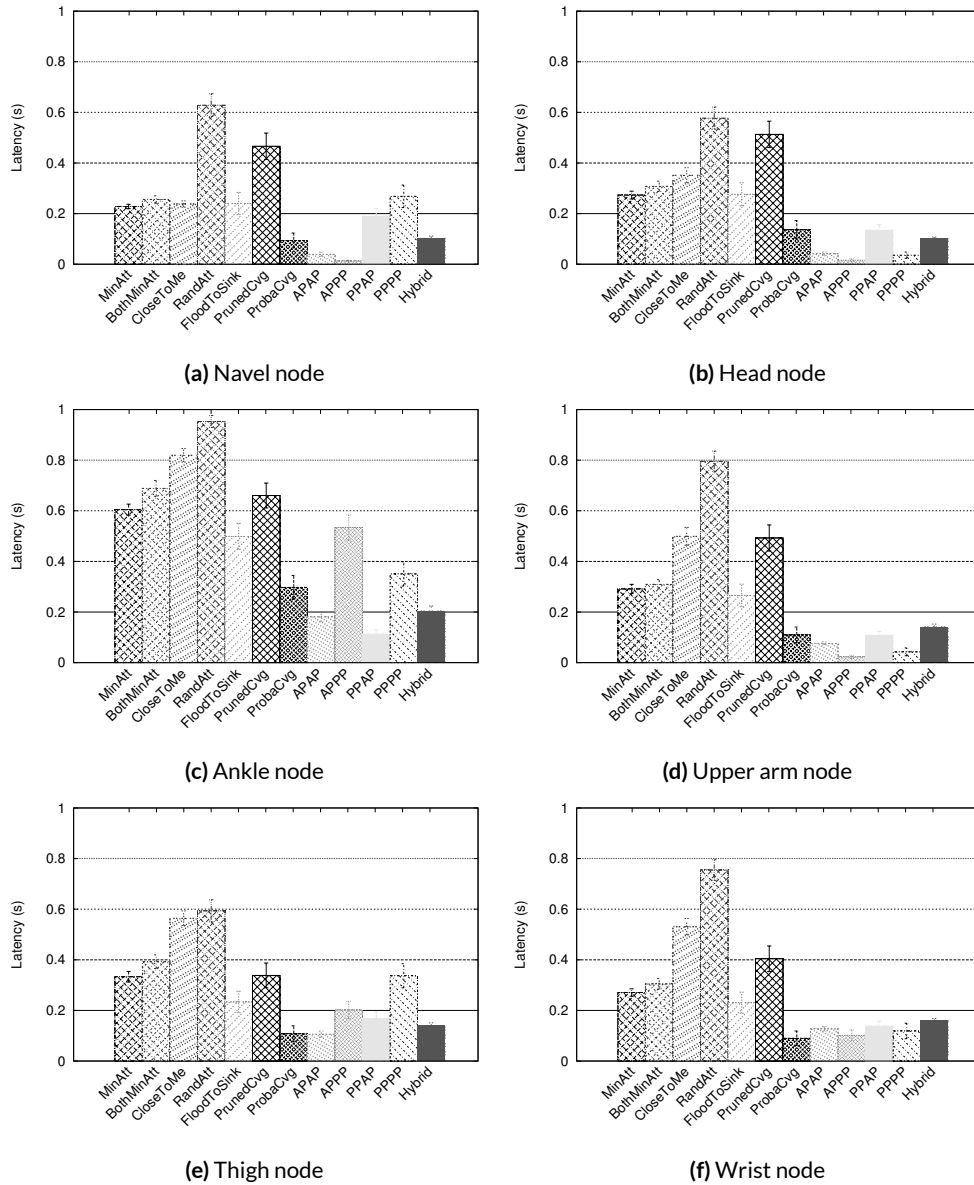


Figure 3.12: Latency per node for all converge-cast strategies

In the static and irregular postures (e.g. *sleep* and *wearing jacket*) messages spend more time to reach the *Sink* node than in postures with higher mobility (e.g. *running*). In a static posture, parent nodes could be unreachable for sources, hence packets are lost and delay increases. *Run* posture presents the highest mobility posture: even with an intermittent connectivity, nodes are able to receive and forward messages to different neighbors which increases the probability to reach *Sink* node. Differently, in case of *gossip-based*, this overloads the network and causes

packets loss and high latency.

For our novel strategy, for all postures, it never presents the highest end to end delay and is very close to the best delay. This leads to conclude that *Hybrid* strategy is more flexible and reliable to human body postures.

Figure 3.12 presents end to end delay per node. Ankle node is the most concerned by a high end to end delay. Indeed, its position makes that its packet is necessarily forwarded by an intermediate node to *Sink* node. The node at tight is the next one to be concerned.

Similar to results per posture, *attenuation-based* strategies show the highest latency for all nodes.

For *multi-path-based* strategies, nodes, like in head and upper arm, that are close to *Sink* node, show an insignificant delay. For example with *APAP* strategy, *Sink* node is one of the pre-defined parents, hence, packet is directly forwarded to its final destination.

TRAFFIC LOAD EVALUATION FOR CONVERGE-CAST STRATEGIES

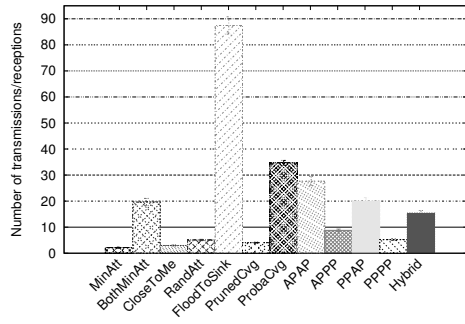
Traffic load is represented as the number of transmissions and receptions. It reflects the channel load and gives indications about energy consumption, devices autonomy and sensors capability to rely on a reduced size battery.

Figure 3.13 compares transmissions and receptions number per posture for each strategy, while figure 3.14 shows number of transmissions and receptions per node.

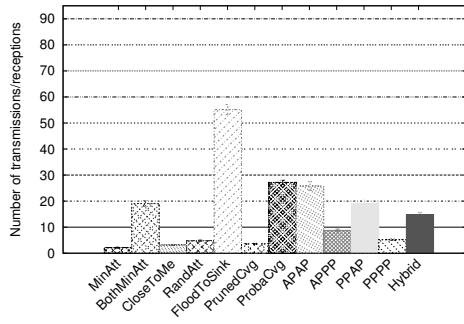
Attenuation-based strategies present a low number of transmissions and receptions because data packets follow a unicast communication. Except for *BothMinAtt* strategy that shows a higher number because each node forwards the message to two neighbors contrary to the other *attenuation-based* strategies. Recall that the number of transmissions and receptions includes only data packets.

For *gossip-based* strategies, *FloodToSink* and *ProbaCvg* strategies present a huge number of transmissions and receptions for all postures. For *FloodToSink*, is three times more, in average, than the other strategies because nodes continue to forward each received message while its TTL is greater than 1. Transmissions and receptions number decreases with *ProbaCvg* strategy thanks to the probability of transmission P , but it is still high compared to the other strategies. For *PrunedCvg* strategy, forwarding the packet to only one randomly chosen next hop, decreases significantly the number of transmissions and receptions. However, looking back to results about PDR, this can not be considered as an advantage.

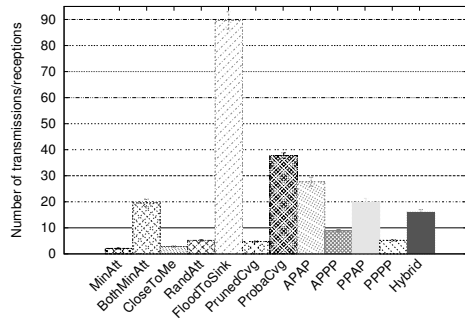
Considering *multi-path* strategies, the number of transmissions and receptions is reasonable. Forwarding packets based on predefined paths allows to control packets copies in the network. *APAP* strategy shows a high number of transmissions and receptions within all the postures



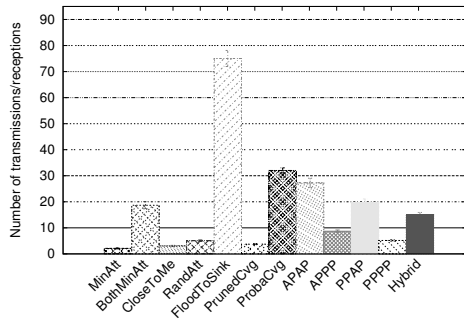
(a) Walking posture



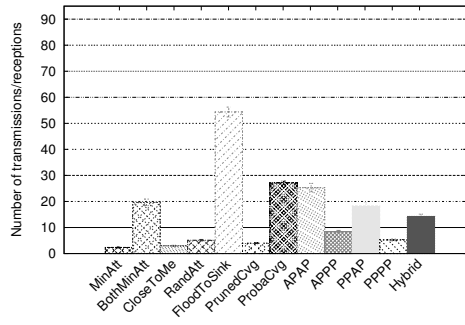
(b) Running posture



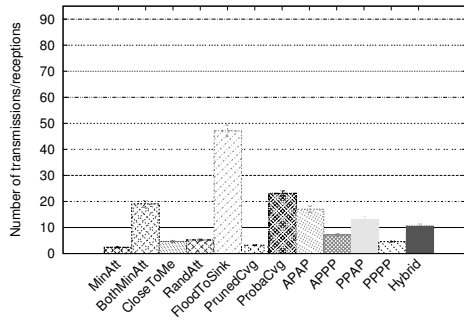
(c) Walking weakly posture



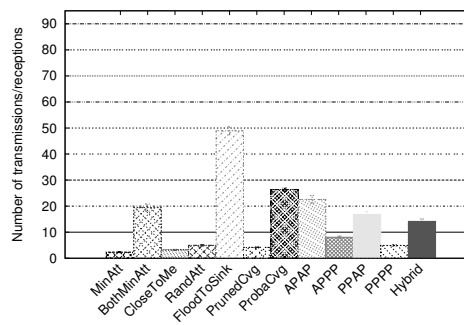
(d) Sitting posture



(e) Lying posture

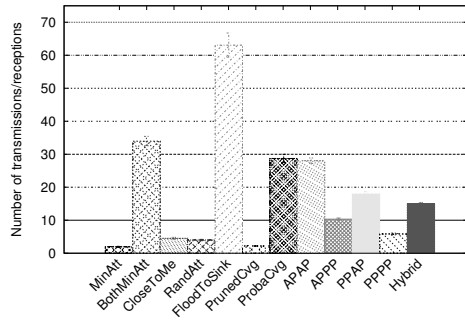


(f) Sleeping posture

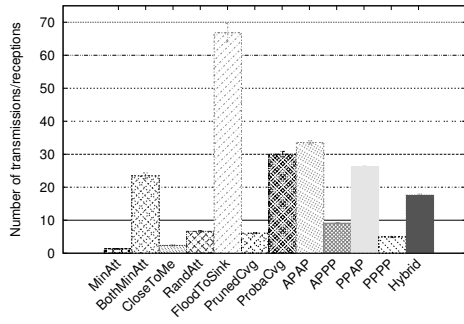


(g) Wearing a jacket posture

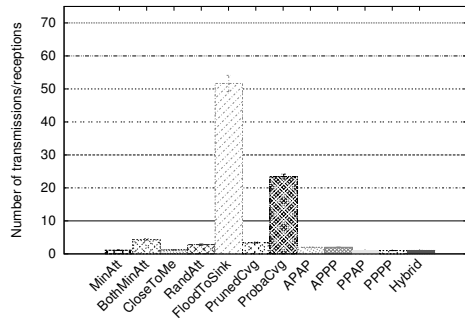
Figure 3.13: Traffic load per posture for all converge-cast strategies



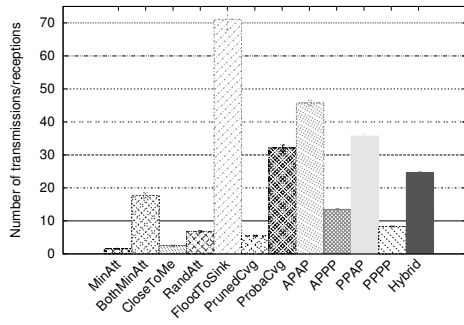
(a) Navel node



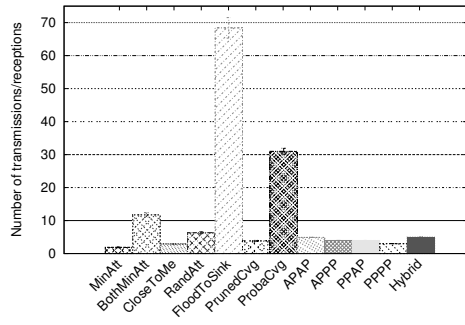
(b) Head node



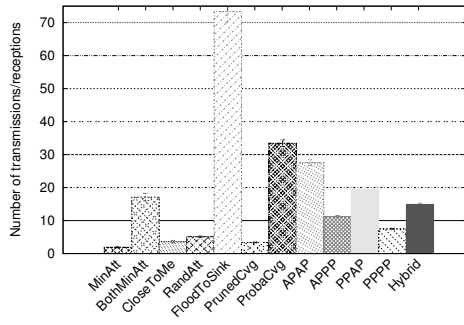
(c) Ankle node



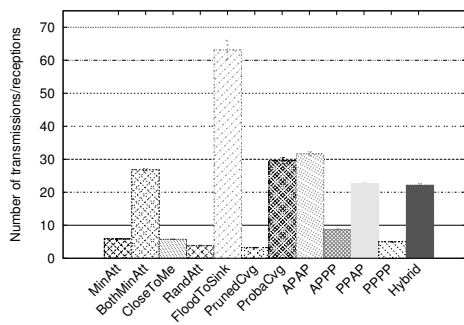
(d) Upper arm node



(e) Thigh node



(f) Wrist node



(g) Chest node

Figure 3.14: Traffic load per node for all converge-cast strategies

compared to the other *multi-path-based* strategies because of the choice of two paths to reach *Sink* node.

Hybrid strategy shows a reasonable number of transmissions and receptions.

Graphs show that ankle node participates less than the other nodes in the communication. Especially for *multi-path-based* strategies, where ankle node only forward its own packet and is never designated as forwarder.

SUMMARY

Table 3.1 reports the average values for all runs, all nodes and all postures per strategy for one single packet transmission. We can classify, from table 3.1, protocols in 4 groups presented in figure 3.15

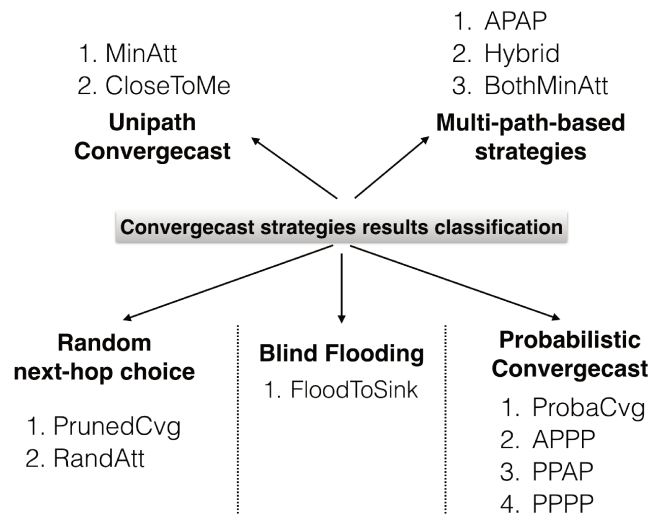


Figure 3.15: Converge-cast protocols classification based on simulation results

The first group, containing *RandAtt* and *PrunedCvg*. Both are based on a random choice of the next hop which results on the lowest PDR. In addition, these strategies present a high latency because the loss of a packet is penalized by a high delay.

FloodToSink doesn't belong to a specific group. It is the unique strategy that is based on full broadcast to reach *Sink* node. From results from the previous sections and from the summary table 3.1, we can conclude that this strategy is not adapted to converge-cast in WBAN. Not only it has a low PDR (72.85%) but also the highest number of transmissions and receptions.

The second group, containing *ProbaCvg*, *APPP*, *PPAP* and *PPPP* where a probabilistic choice guides the converge-cast process. *PPAP* stands out with a bit higher PDR because intermediate nodes forward to all parents that usually one of them is the *Sink* node.

	PDR (%)	Latency (ms)	Traffic (pkt)
<i>MinAtt</i>	97.61	333.4	2.23
<i>BothMinAtt</i>	99.52	376.5	19.30
<i>CloseToMe</i>	96.09	500.4	3.26
<i>RandAtt</i>	64.09	717.2	5.07
<i>FloodToSink</i>	72.85	290.6	65.37
<i>PrunedCvg</i>	53.42	479.0	3.93
<i>ProbaCvg</i>	87.04	139.0	29.75
<i>APAP</i>	98.90	95.1	24.77
<i>APPP</i>	88.42	148.1	8.40
<i>PPAP</i>	94.76	141.8	18.14
<i>PPPP</i>	83.09	192.1	5.07
<i>Hybrid</i>	98.76	141.1	14.33

Table 3.1: Average PDR, latency and traffic load for all converge-cast protocols

The third group, containing *MinAtt*, *CloseToMe*. Both of them represent uni-path converge-cast, from source to *Sink* node. When looking to the PDR, *MinAtt* outperforms slightly *CloseToMe*, however, looking to the latency, with *CloseToMe*, a higher end to end delay is observed. This is due to the fact that with this latter, source nodes may not choose to forward the packet to *Sink* node because another node closer has responded to the request too.

The last group, containing *BothMinAtt*, *APAP* and *Hybrid*. Our novel converge-cast strategy *Hybrid* shows a competitive average end to end success rate. Its performance exceeds those of *gossip-based* in terms of PDR, *APAP* strategy in terms of energy consumption and *attenuation-based* strategies in terms of delay even if both, *attenuation-based* strategies and *Hybrid* strategy, use a timer and delay transmissions.

3.5 CONCLUSION & DISCUSSION

In this chapter, we implemented and evaluated through extensive simulations the performance of 11 various WSN and DTN-inspired converge-cast strategies that we classified to three different approaches: Gossip-based, Attenuation-based and Multi-path-based strategies.

Our simulations were conducted with OMNeT++ simulator enriched with the Mixim framework and a WBAN realistic channel model recently proposed in [89] and detailed in section 2.7.2.

Looking to simulation results, we observed that *attenuation-based* strategies show a high end to end success rate. This delay is due to the exchange of control messages before taking the decision to forward or not data message.

Gossip-based strategies show a low PDR in addition of an important traffic load. We conclude that these strategies are not adapted for converge-cast in WBAN environment. A low end to end success rate due to collisions and a high energy consumption are unacceptable in a WBAN context.

In *multi-path-based* strategies, *APAP* strategy shows a good performance despite a slight increase in traffic load.

We further proposed a novel converge-cast strategy called *Hybrid* that presents a good compromise in terms of end-to-end delay, resilience to mobility and energy consumption.

Hybrid converge-cast scheme is based on: an *attenuation-based* approach with PING broadcast, a *multi-path-based* approach with pre-defined paths, and a *gossip-based* approach with broadcast if parent nodes are not in range. Consequently, *Hybrid* strategy gets to reach a better PDR than *gossip-based*, a better latency than *attenuation-based* strategies and a less traffic load than *APAP* strategy. A trade-off is respected with our novel protocol *Hybrid*.

Several future directions are opened by our research. The first direction is to identify the impact of MAC layer in order to improve the best of our strategies by combining them with cross-layer techniques developed for WBAN [46, 36, 26].

Another direction is to add to the studied strategies the total-order features. Although this problem is crucial for medical applications it has never been investigated in WBAN context.

4

Broadcast strategies in WBAN

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4.1 INTRODUCTION

In this chapter, we investigate the *broadcasting* problem in which a node, typically the *Sink* node, tries to send a packet to all other nodes in the network at minimal cost.

Broadcasting is fundamental for the application level, for reconfiguration or for transmitting emergency messages, as well as, for network-level operation like route discovery, maintenance of the routing tree if needed. Toward optimizing the broadcast, two key features of wireless communications should be carefully addressed. One is the broadcast nature of wireless medium; a transmission of a message could be heard simultaneously by multiple neighboring nodes which can speed up the broadcast process. The other one is wireless interference/collision; a node can not receive a message if more than one neighboring node are transmitting at the same time.

We implement and analyze the behavior of 7 broadcast strategies adapted from DTN and WSN literature. Then, we propose two alternative strategies from the analysis of the strengths and weaknesses of the different approaches. We exploited on-body packet broadcasting issues on the presence of ultra-short wireless range and postural body movements.

We show through simulation that communication strategies coming from the DTN and WSN areas cannot be transposed without adaptation. We enriched the Omnet++ simulator with a WBAN-specific channel model (section 2.7.2) and use this model to evaluate the 9 broadcasting algorithms, including our own proposals, with respect to their ability to cover the whole network, their completion delay, their cost in terms of energy consumption and their capability to preserve multiple packets order (i.e. FIFO order broadcast).

Our study shows that there is a subtle compromise to find between verbose strategies that achieve good performance at the cost of numerous transmissions, ultimately provoking collisions and more cautious solutions that miss transmission opportunities because of mobility.

The chapter is organized as follows: section 4.2 introduces the context and the broadcast problem and presents relevant related works. Section 4.3 presents the various broadcast strategies, including two original contributions, that we have compared through simulation in section 4.4. Section 4.4 presents and compares simulation results of the broadcast strategies with respect to network coverage, latency, traffic volume and energy consumption.

4.2 CONTEXT

Broadcasting algorithms for multi-hop networks [172, 215] can be classified into two major categories: *dissemination* (or *flooding*) algorithms require no particular knowledge of the network versus *knowledge-based* algorithms, which use some information of the network mobility to predict spatiotemporal connectivity and to reduce the number of transmissions. Dissemination algorithms tend to generate multiple copies of the same message, which explore all paths in parallel and improve mechanically the delivery probability while reducing the delay until congestion appears. Such strategies generate a large number of unnecessary transmissions and are not energy-efficient. Understanding and using the nodes mobility pattern leads to a better

efficiency, but acquiring the necessary information has a cost and there is a subtle balance to find between duplicate data packets and control messages.

In their papers [151, 202], Ni *et al.* and Tseng *et al.* name and analyze the *broadcast storm* problem that happens in mobile ad-hoc networks: blind flooding generates numerous transmissions all over the network, causing collisions, increasing contention and redundant transmissions. To alleviate this effect, each node can condition its retransmission to a constant probability and takes a forwarding decision based on the number of copies received during a certain time frame, on the distance between the source and the destination or on the location of the nodes if it is available. They also examine the effect of partitioning the network in 1-hops clusters, the cluster heads forming a dominating set among the network. The dominating sets-based approaches will be the source of numerous contributions, but is not really relevant in WBANs, as the size and the diameter of the network remain limited. However, due to the node mobility as well as the underlying randomness of broadcast process such number may vary significantly over different nodes and can also be hard to estimate making the optimization of forwarding probability difficult.

Many works have explored the probabilistic flooding approach, also called *gossiping*. Haas *et al.* [79] identify the existence of a threshold on the forwarding probability below which gossiping fails to deliver the message. Authors also present two other derivatives strategies from the basic gossiping protocol. In the first one, they introduce threshold on the number of neighbors and for the second one they introduce a threshold on the number of the senders of each message. Sasson *et al.*, in [182] use percolation theory to characterize this phase transition threshold on random graphs. Neither of these works are directly applicable to WBANs, as the mobility pattern is very different, but they both show that the networks shape and dynamics have an influence on the optimal forwarding probability.

In [198], Tang *et al.* present R^2 , a broadcast protocol. R^2 splits the message into mini-messages and then couples a fine-grained Random scheduling with Random linear network coding for broadcasting the mini-messages to achieve an optimal broadcast latency comparing to a random scheduling as in [79, 202]. A random scheduling is applied on mini messages using a uniform forwarding probability. Then mini messages are transmitted in Random scheduling with Random linear network coding fashion i.e all nodes forward coded mini-messages formed from random linear combinations of all previously received messages. Authors take into account mobility constraints in MANET networks by considering a rapid change in network topology and show that R^2 can achieve an order-optimal broadcast latency. Authors focus on latency however the cost in terms of network overload was not discussed.

Vahdat *et al.*, in [211] were among the first to consider that end-to-end connectivity was not guaranteed permanently. They rather consider a network formed of different connected groups of nodes that eventually meet. They introduce *epidemic routing*, whose first step consists in

disseminating information inside a group through basic flooding. When two nodes meet, they exchange a *summary vector* containing the messages ID they already possess and then exchange only the missing messages that will propagate through new clusters this way.

In [138], Miyao *et al.* propose a broadcast protocol that is based on a fault-tolerant topology control algorithm to enhance reliability and that uses overhearing, appropriate timeout and table sharing scheme to reduce unnecessary transmissions and hence to reduce energy consumption. However, authors assume an ideal MAC layer and mobility wasn't discussed.

In DTN, nodes can communicate even if there is no direct link between a couple of nodes, DTN use mobility to carry the information.

In [84], the authors compared various strategies for controlling flooding in delay tolerant networks, assuming that nodes have no knowledge about their location or their mobility. They compare performance of probabilistic approaches with different approaches limiting flooding impact using a time to live, expressed either in number of hops, or as an expiration date. Unsurprisingly they show that these strategies can effectively reduce the load induced by flooding the network without increasing significantly the completion delay, or the failure probability.

Spray and Wait, [190], is an original routing strategy that decomposes the transmission process in two phases. In the spray phase, multiple copies of the message are sent in the network with a flooding-like mechanism. Then the nodes who hold copies of the message start waiting until they meet the destination to which they will transmit the message directly. Spray and Focus [191] goes one step beyond by letting nodes that hold one of the message copies forward it using an utility function, rather than waiting to meet the destination. These strategies are not flooding strategies, however they show how controlling and limiting the number of copies of the same message that travel in the network affects the delivery performance.

In the *k-neighbor* broadcast scheme [72], a packet is retransmitted if and only if the number of neighbors present exceed a threshold, K , and if at least one of these neighbors did not receive the message yet. Even if the implementation is different, we find back here the concepts behind epidemic routing and the notion of not systematically transmitting a packet to reduce the number of transmission.

In [171], Ros *et al.* discuss reliable and efficient broadcasting in vehicular ad hoc networks which is an adaptation of the parameterless broadcast in static to highly mobile ad hoc networks protocol [103]. Their protocol uses periodic beacon messages to acquire local position information. These information relieve whether cars belong to a connected dominated set or not. In case yes, vehicular cars use shorter waiting period before possible retransmissions. In addition, authors use an acknowledgement mechanism by adding information about last received messages piggybacked to the beacons which avoid unnecessary retransmissions. A similar approach is used with the implemented strategy *EBP*.

In WBAN, broadcasting is not the primary traffic pattern concerned in the literature [32,

144, 49]. Most works about communication protocols [125, 134] use broadcast to exchange control messages and to enable route discover between a source and a destination. In addition, most of them refer to a simple flooding protocol.

Based on the amount of knowledge we have, rare are the papers that consider broadcast for data message [229, 57]. In addition, these works don't target the network layer with flat broadcast strategies as evaluated in our current work. For example, in [57], a cross-layer approach is discussed.

4.3 BROADCAST PROTOCOLS DESCRIPTION

As forwarding/routing in multi-hop networks has been very active in the past decades, several strategies are available when it comes to broadcasting. However, there is no definitive answer with respect to the specificities of the WBAN context yet. Our goal, in this work is to compare the classical strategies categories to shed light on their strengths and weaknesses.

We consider that the *Sink* node initiates the communication at the application layer, which is then sent throughout the network. When a node receives a broadcasted packet, it needs to take a decision whether to transmit it to the application layer, to forward it and to which of its neighbors and when, or to discard it. It bases its decision on the broadcasting algorithms and on the packet characteristics. Nodes may examine the packet's Time-To-Live (TTL) to evaluate how long it has been in the network, or its sequence number, which can give an indication on whether the packet has already been received or not.

Here, we are interested in network related aspects only and make abstraction of the system aspects such as the memory required to store all received sequence numbers. Practical solutions to these issues exist and may be appropriate or not depending on the scenario. For example, storing only the last sequence number per source is valid when dealing with successive updates that supersede each other. TCP-like solutions are also possible when all messages need to be received.

As the literature suggests, understanding the nodes relative mobility can improve the forwarding decision, but capturing nodes mobility has a cost. It either requires a precise nodes localization mechanism, which is typically achieved by measuring round-trip time of flights between couple of nodes in IR-UWB networks, or relies on *hello messages* to learn connection/disconnection patterns. In both cases the gain acquired by optimizing the broadcast process can quickly be lost to control traffic.

In the rest of this article, we compare the performance of the following categories of strategies:

Flooding designates the simplest strategy: nodes forward each received packet as long as the packet's TTL is greater than 1 and decrement this value in the packet by 1 upon transmission.

Plain Flooding is more restrictive: using sequence number, a received packet is delivered to the application layer and forwarded if and only if it has never been received before. Redundant copies are discarded and each node emits each packet at most once.

Probabilistic Flooding ($P=0.5$) : nodes broadcast packets according to a constant probability, P . The choice of the correct value for this threshold depends on the scenario, which makes this type of solution difficult to adapt in practice. For our evaluation scenarios, we realized simulations for various values of the P parameter that show the same trend: the lower the probability, the worse the network coverage is. In this paper, we chose to present results for a probability $P = 0.5$ to show the compromise between a very cautious strategy failing to cover the network (e.g. $P = 0.3$) and flooding ($P = 1$)

Probabilistic flooding ($P_{new}=P_{old}/2$) : nodes decide to broadcast each packet according to a probability P that is divided by 2 every time the same packet is re-broadcasted. The probability depends on each node and is not embedded in the packets; nodes maintain a local table of packets identification and associated probabilities. In our simulations, the initial forwarding probability is set to 1.

Pruned Flooding (K) : each node forwards each packet only to K neighbors, chosen randomly per packet according to an uniform distribution. The choice of the parameter, K has a strong influence on the protocol performance, as confirmed by our simulations. This strategy requires a node to identify its neighbors and hence induces control traffic. It also transforms the broadcasting process into multiple unicast transmissions, but can, in practice, be implemented over a broadcast medium by embedding the designated neighbors list in each packet's header.

Tabu Flooding : each packet contains the list of nodes it has been forwarded by. This information is, of course, different for different instances of the same packet and issues related to the maximum packet size can be ignored given WBAN's classical diameter. Each node uses this information to forward packets only to yet uncovered nodes, which requires nodes to identify their neighbors and, as in *Pruned Flooding*, may transform the broadcasting process into multiple unicast transmissions.

EBP (Efficient Broadcast Protocol) ($I; K$) [72]: nodes only broadcast a packet when they are surrounded by at least K neighbors, and if at least one of these neighbors has not

received the packet yet. Nodes exchange every I seconds *Hello* packets containing their identification and the list of packets they already received, which can be limited to the last sequence number received depending on the application.

Two maps are used: Neighbor-map to save the address of all the “neighbor” nodes from which it receives a message (both data and hello messages indicate the presence in the node radio-range) and for each neighbor if it is already covered, and Wait-map to store the messages which are waiting to be broadcasted.

Each time a message is received, the neighbor map is updated and then its size is compared with a threshold K . If the number of neighbors (the size of the map) is equal to or higher than K and at least one of the neighbors has not yet received the data message, then, the received message (and the other messages stored in the wait-map) are broadcasted, otherwise the message received is stored in the wait map.

The neighbor-map time is settable: it’s the time after which the source address of a neighbor is deleted from the neighbor map.

In the original *EBP*, the threshold value, K , was considered constant and uniform across the network. In a WBAN environment, adapting this value to the location of nodes in the network seems natural, as some nodes are more natural forwarders than others. In the implementation we evaluate in this work, K is set to 2 for the *Sink* node (chest), to 2 for the head and ankle (peripheral nodes) and to 1 for the other nodes (center nodes).

Two *Hello* frequencies I are considered during simulations: every $I = 0.25 s$ and $I = 0.5 s$.

4.3.1 NOVEL BROADCAST PROTOCOLS

MBP: MIXED BROADCAST PROTOCOL

$(NH; Q; T)$: we proposed this strategy in [28] as a mix between the *dissemination-based* and *knowledge-based* approaches. The broadcast begins as a basic flooding algorithm (i.e *Flooding* strategy). When a node receives a message, it checks the number of hops δ this message has traveled since its emission by the *Gateway*, either embedded in packets as an explicit value, or using the TTL, and compares it to a threshold, NH :

- As long as $\delta < NH$, nodes forward the packet, using simple flooding, broadcasting the packet to all neighbors in range.
- When $\delta \geq NH$, nodes wait during a time T to receive up to Q acknowledgments sent by neighbors (see below).

- if it receives a number of acknowledgments greater or equal than Q , the node stops rebroadcasting the message.
- if it fails to receive Q acknowledgments within T , it broadcasts the packet.
- When $\delta > NH$, nodes send, in addition, an acknowledgment to the node it received the packet from. Note that in a real implementation, these acknowledgments could be implicit when nodes decide to rebroadcast the packet.

This algorithm depends on three main parameters to continue or stop the broadcast: NH , the threshold on the number of hops traveled so far, Q , the number of expected acknowledgments and T the timeout that triggers the next forwarding attempt. All parameters have an influence on the algorithm performance that we evaluated through simulation. Concerning Q , we determined that the best performance was achieved with different values according to node position: for example, for non natural forwarder nodes like head and ankle nodes, Q should be set to 0. In our simulations we set $Q = 0$ for the head and ankle nodes, $Q = 2$ for the chest node and $Q = 1$ for all the other nodes. The timeout has been set to $T = 0.2 s$. In section 5.4, we show results for NH equals to 1, 2 and 3.

OPTIMIZED FLOODING

In addition to the aforementioned protocols, we introduce here for comparison a new protocol named *Optimized Flooding*. This protocol aims at achieving a better compromise between traffic and performance by limiting packets retransmissions with two counters:

- **cptGlobal** is embedded into each copy of the packet itself. Every time the packet is received by a node that had not received it previously, **cptGlobal** is increased before forwarding to reflect the fact that the packet reached a new node.
- **CptLocal** is a per-packet variable local to each node. It is a local copy of the maximum value of *cptGlobal* that the node has seen so far.

The general idea of this algorithm is to limit packets transmissions with respect to flooding without any additional control traffic, e.g. to identify neighbors. The two counters (*cptGlobal* and *CptLocal*) act as indicators of the behavior of the packet and are used to avoid packets traveling a too long and redundant road (*cptGlobal*) and to avoid ping-pong effects between close nodes (*CptLocal*).

Optimized Flooding limits broadcasting by comparing packets *cptGlobal* values with local *CptLocal* values. When *cptGlobal* is lower than *CptLocal*, the packet instance received has traveled a shorter path than a previous instance and is redundant. Both counters are limited by

a maximum value, $cptMax$, which limits packets journeys. In a conservative approach $cptMax$ is set by default to the number of nodes in the network. Upon reception of a broadcasted packet, each node applies algorithm 3. This algorithm does not need information about nodes neighbors and hence relies only on data packets. It however requires to keep track of the nodes that forwarded instances of the packets, and may require storing a list of forwarders in each packet header.

The intuition behind this algorithm comes from the *Flooding* strategy. The latter shows the best performance of reliability and latency, however it shows a very large number of exchanged messages. So the idea of Optimized flooding is to limit this number of exchanges without influencing the other performances.

With $cptGlobal$, we limit the retransmissions after the total coverage of the network (compared to $cptMax$) while with $cptLocal$ we limit the return of the message between two strongly connected nodes and also we make sure that the nodes rebroadcast the message in the case where there is new information to communicate namely the number of covered nodes.

Optimized Flooding implements the following primitives:

- $Deliver(m \langle SeqNum, TTL, CptGlobal \rangle)$: Each node delivers m to the application level upon receiving m for the first time.
- $Broadcast(m \langle SeqNum, TTL, CptGlobal \rangle)$: All nodes in the network perform a broadcast of the message m in the network.

Algorithm 2 Optimized Flooding algorithm for *Sink* node upon receiving an application message m

- 1: Set TTL
 - 2: Set $SeqNum$
 - 3: Set destination address $destAddr$ ▷ A broadcast address
 - 4: Broadcast(m)
-

4.3.2 PROOF OF CORRECTNESS OF OPTIMIZED FLOODING PROTOCOL

In the following we consider that the WBAN network is model by a connected graph $G = (V, E)$ where V is the set of nodes in the system and E is the set of communication links (edges between nodes in V). We consider a connected graph. That is, it exists a path between every pair of nodes. In simulations, we carefully choose nodes transmission power to respect this characteristic. Note that if the graph is not connected, there is no coverage. In the following we consider that the communication links are reliable (i.e. no packets loss or collisions).

Algorithm 3 Optimized Flooding algorithm: take a forwarding decision when receiving a packet

```

1: procedure UPON RECEPTION( $m \langle SeqNum, TTL, CptGlobal \rangle$ )
2:   if Upon receiving for the first time then ▷ based on  $SeqNum$ 
3:      $cptGlobal \leftarrow cptGlobal + 1$ 
4:      $cptLocal \leftarrow cptGlobal$ 
5:     Deliver( $m$ )
6:     if  $TTL > 1$  then
7:       Broadcast( $m \langle SeqNum, TTL, CptGlobal \rangle$ )
8:     end if
9:   else
10:    if  $cptGlobal$  never increased by this node for this copy of the message  $m$  then
11:       $cptGlobal \leftarrow cptGlobal + 1$ 
12:    end if
13:    if  $cptGlobal = cptMax$  then ▷  $cptMax$  = Number of nodes in the network
14:      Discard  $m$  ▷ All nodes have received the packet
15:    else
16:      if  $cptGlobal \leq cptLocal$  then ▷ a better instance has been received before
17:        Discard  $m$ 
18:      else
19:        if  $TTL > 1$  then
20:           $cptLocal \leftarrow cptGlobal$ 
21:          Broadcast( $m \langle SeqNum, CptGlobal \rangle$ )
22:        else
23:          Discard  $m$ 
24:        end if
25:      end if
26:    end if
27:  end if
28: end procedure

```

The Optimized Flooding protocol aims at solving the broadcast problem defined informally in [157] *The broadcast operation is initiated by a single processor r_o , called the source. The source has a message, initially kept on a special input buffer. This message needs to be disseminated from the source to all vertices in the network.*

In the following we formalize the broadcast problem inspired by the definition proposed in [50].

Definition 3 (Broadcast). *Let $G = (V, E)$ be the communication graph modeling a network and Sink be the node that initiates the broadcast. A protocol implements the broadcast problem if the*

following properties are satisfied.

- *Validity*: If a message m is broadcasted by Sink then m is received by every node in V .
- *No duplication*: No message is delivered at the application level more than once.
- *No creation*: No message is delivered at the application level unless it was broadcasted by a Sink node.

NOTATIONS AND DEFINITIONS

In this section we introduce the notations and definitions used in our correctness proof.

Definition 4 (eccentricity). The eccentricity $\epsilon(v)$ of a graph vertex v in a connected graph $G = (V, E)$ is the maximum graph distance between v and any other vertex u of G .

In this work we are interested in the eccentricity of the Sink node $\epsilon(\text{Sink})$.

Definition 5. Let $G = (V, E)$ be the communication graph modeling a network. For any i in V let $N(i)$ be the set of neighbors of i and let $|N(i)|$ be the degree of i denoted d_i .

Assumption 2. In the following proofs we consider that TTL is greater than the eccentricity of the $\epsilon(\text{Sink})$.

Lemma 5. If the Sink broadcasts a message, m , then nodes in $N(\text{Sink})$ eventually receive m .

Proof. Suppose Sink broadcasted the message m . Assume $\exists j \in N(\text{Sink})$ such that j didn't receive m . This assumption is false since we assume that links are reliable (no lost messages). \square

Lemma 6. If a node i broadcasts a message m then nodes in $N(i)$ eventually receive m .

Proof. Suppose i broadcasted the message m . Assume $\exists j \in N(i)$ such that j didn't receive m . This assumption is false since we assume that links are reliable (no lost messages). \square

Lemma 7 (validity). If the Sink broadcasts a message m , then all nodes in V eventually receive m .

Proof. Suppose that there is a node j such that j didn't receive the message m . This implies that all neighbors of j didn't broadcast the message.

Let $i \in N(j)$ such that i received m but didn't broadcasted m (the case where i didn't received the message is discussed later). There are the following cases:

case 1 : $cptLocal_i > cptGlobal$ (Line 16) \implies i already broadcasted m with $cptGlobal = cptLocal$. This and the perfect communication links imply that j received m .

case 2 : $cptGlobal = cptMax = |V|$ (Line 13) $\implies \forall k \in V$ k received the message m . This implies that also j received m .

case 3 : $TTL = 1$ (Lines 6, 19) $\implies TTL \geq \epsilon(Sink)$ then there is a message m with $TTL > 1$ already broadcasted by i . It follows that j received the message m .

From these cases it follows that if a neighbor of j received the message then also j received it.

Suppose now that no neighbor of j received the message. Let k be a neighbor of j in this situation and let d the shortest distance from k to the *Sink*. By applying the same reasoning as previously, it follows that none of neighbors of k received the message. So, no neighbor of k at distance $d - 1$ from the *Sink* received the message. Applying recursively the same reasoning it follows that nodes at distance 1 from the *Sink* did not receive the message which contradicts Lemma 5. \square

Lemma 8 (no duplication). *If a node i receives a message m then m is delivered at the application level only once.*

Proof. When a node i receives the message m for the first time then i delivers m (Line 5). When the message is a duplicate of an already received message then i triggers either a broadcast or a discard, depending on $cptGlobal$ and $cptLocal$ values, and does not deliver (Lines 9 – 27). \square

Lemma 9 (no creation). *If a node i receives a message m then m has been broadcasted by the *Sink*.*

Proof. Assume i receives a message m that has not been broadcasted by *Sink*. This means that the message has been created by another node or there was a steal message in the channels. The first assumption contradicts the algorithm since no node (except the *Sink*) creates a new messages. The second assumption contradicts the hypothesis that the links are reliable. \square

4.4 PERFORMANCE ANALYSIS OF BROADCAST STRATEGIES

We implemented the algorithms described in section 4.3 in a WBAN scenario in the Omnet++ simulator [213, 212]. Omnet++ provides a set of modules that specifically model the lower network layers of WSN and WBAN, thanks to the Mixim project [109]. It includes a set of propagation models, electronics models and power consumption models, as well as diverse medium access control protocols.

4.4.1 SIMULATION CONFIGURATION

Before actually comparing algorithms, we need to select general parameters values in order to provide for a fair comparison. This includes some protocol-specific parameters described above, as well as more general parameters such as the nodes transmission power, or the maximum allowed TTL.

We first tested the different protocols for the broadcast of a single data packet from the source. This elementary scenario allows us to compare protocols general behavior excluding scalability issues. Each data point is the average of 50 simulations run with different seeds. We used Omnet++ default internal random number generator, i.e. the Mersenne Twister implementation (cMersenneTwister ; MT19937) for the uniform distribution, with different initialization seeds for each run, and the normal distribution generator (cNormal) for the signal attenuation.

On the top of the channel model described in section 2.7.2, we use the standard protocol implementations provided by the Mixim framework. In particular, we used, for the medium access control layer, the IEEE 802.15.4 implementation. The sensitivity levels, header length of the packets and other basic information and parameters are taken from the IEEE 802.15.4 standard.

SETTING THE TRANSMISSION POWER

Naganawa et al. studied in their paper [89] a cooperative transmission scheme: two-hop relaying scheme. Using the simulated path loss, the performance of such scheme were evaluated by comparing the outage probability using different relay nodes against a direct link between a source and a destination. They advocate for the use of multi-hops communication, adding to this, a significant decrease of the transmission power. If we consider multi-hop forwarding, we may therefore wonder what is the minimal transmission power that allows protocols to achieve an acceptable performance.

For each strategy, we evaluate the impact of the transmission power on its capability to cover the network. As a reference, we also include evaluation of the "1-hop" strategy in which nodes do not forward messages. Figures 4.1 and 4.2 show the percentage of covered nodes when the transmission power increases from -60 dBm to 0 dBm in two different representative postures: walk and Sleeping.

Hence we compare the performance of the different strategies in search for the minimum transmission power that allows reasonable communication for a receiver sensitivity of -100 dBm considering the channel attenuation. We seek for the value of the transmission power that ensures the network is connected over time, while limiting energy consumption and devices temperature.

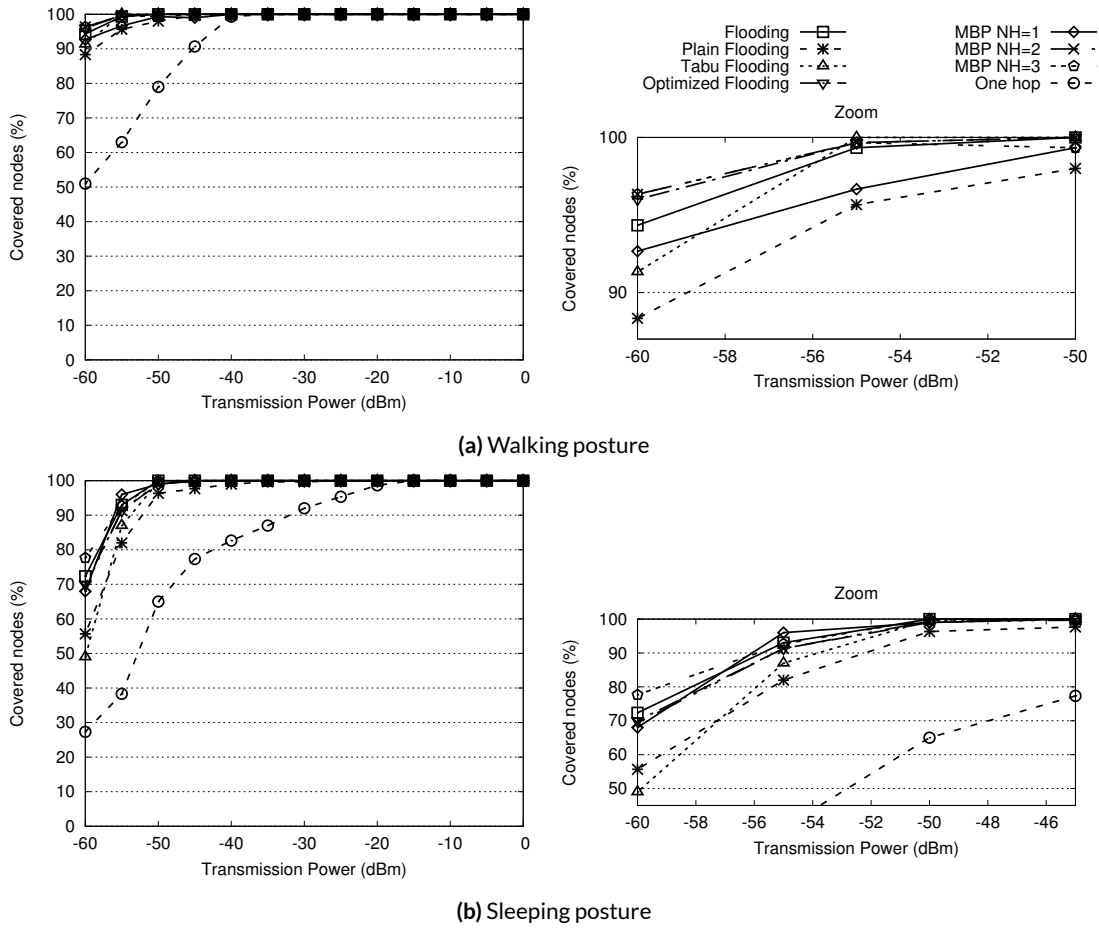


Figure 4.1: Percentage of covered nodes in function of nodes transmission power (Broadcast protocols: First group)

The first conclusion that comes from these figures is that using multi-hop communication allows to reduce the transmission power drastically. At -55 dBm, most protocols achieve a fair performance, covering most of the network, while the 1-hop strategy requires a power of -40 dBm to reach similar performance. In the rest of this article we therefore set the transmission power of nodes to -55 dBm. Note that the *Pruned Flooding*, *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$) and *EBP* strategies are more sensitive to the transmission power may have lower performance than other algorithms, depending on the parameters values.

The set of links that most protocols rely on is represented on Figure 4.3. The link between the head and the wrist exists, but is seldom used.

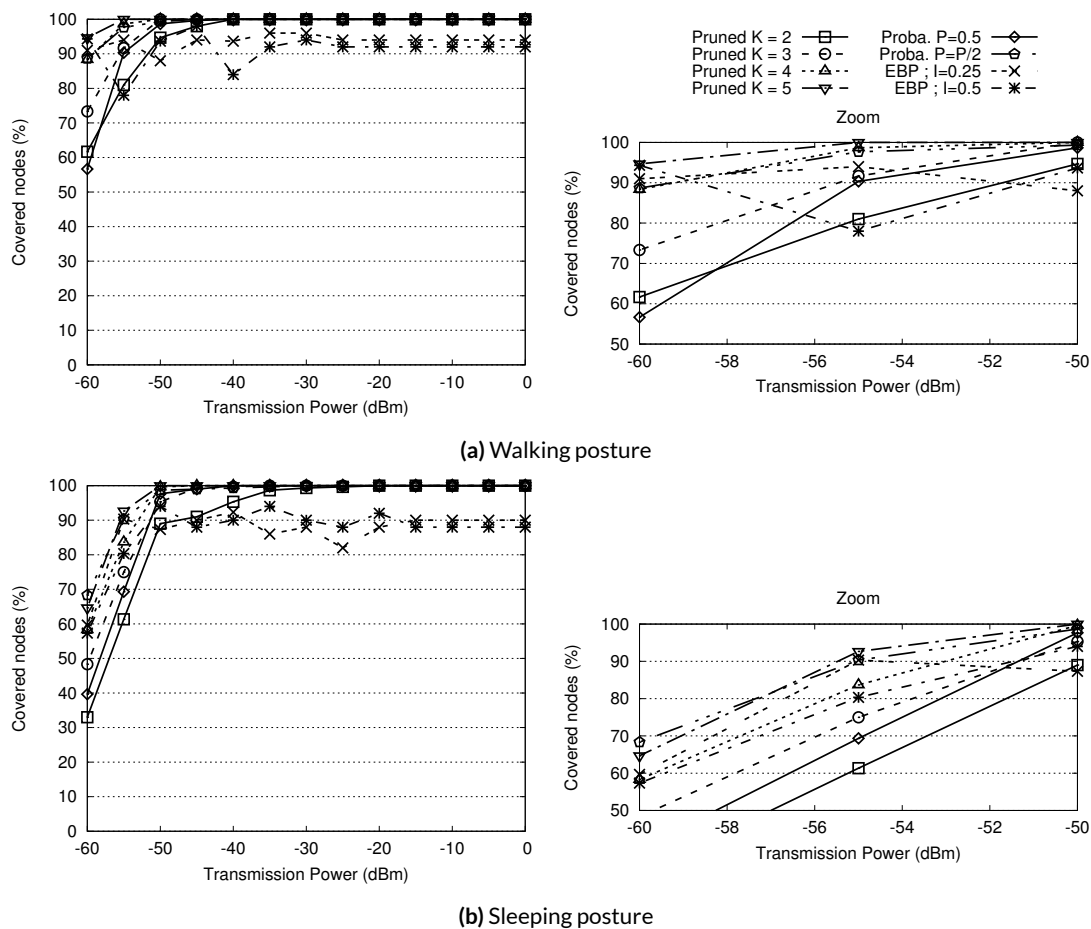


Figure 4.2: Percentage of covered nodes in function of nodes transmission power (Broadcast protocols: Second group)

SETTING THE MAXIMUM TIME-TO-LIVE (TTL)

The Time-To-Live (TTL) mechanism limits packets retransmissions independently of the broadcast algorithm. A high TTL value results in a huge number of packets traveling in the network, ultimately provoking queuing and collisions, while a low value limits the decision power of the different algorithms. Setting this value in a low diameter mobile network may be uneasy, that's why we rely on simulation results to find a fair value. In our implementation, the TTL is decremented from the first transmission, which means that a packet whose initial TTL value is equal to 1 will only be emitted once and never be forwarded.

Figure 4.4 shows the percentage of covered nodes in function of the packets initial *TTL* in the walking posture. This posture corresponds to a soft and regular motion, in which the source has at least three direct neighbors.

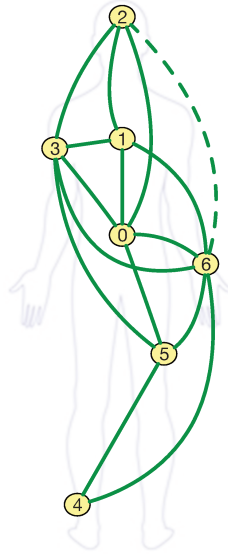


Figure 4.3: Set of links used by the broadcast protocols when the transmission power is set to -55 dBm

When TTL is equal to 1, 63% of the network is covered for nearly all strategies, except *EBP* variations. *EBP* shows a lower performance in this situation due to the amount of control packets that cause collisions on the one hand and the necessity to reach a certain number of neighbors before transmitting a packet on the other hand. With a high Hello frequency I the control traffic causes additional delays and collisions, while decreasing this frequency leads to more frequent neighbors timeout expirations.

The strategy *Flooding* represents a reference, as nothing prevents retransmission as long as the TTL is positive. It therefore achieves a quite high coverage performance in this low-traffic scenario where collisions are unlikely. *Plain Flooding* has a similar behavior when the TTL is low but fails to improve when the TTL gets greater than 3 because it filters out packets as soon as they have been received once and hence does not benefit from a TTL increase.

For *MBP*, NH represents the threshold that separates *Plain Flooding* from acknowledged broadcasting. As soon as NH reaches a value of 2 hops, Figure 4.4 shows that *MBP* has a satisfactory performance evolution. *Optimized Flooding* also shows comparable performance. For example, with $TTL = 4$, 98.6% of the network is covered. The fact that these strategies both achieve a performance level comparable to *Flooding* while they prevent packets retransmissions much sooner, indicates that they are able to find the correct compromise between traffic volume and coverage.

For *Pruned Flooding* strategy, the choice of the number of random receiver among the neighbors, K , has a direct influence on the coverage probability. Figure 4.4 shows results for K vary-

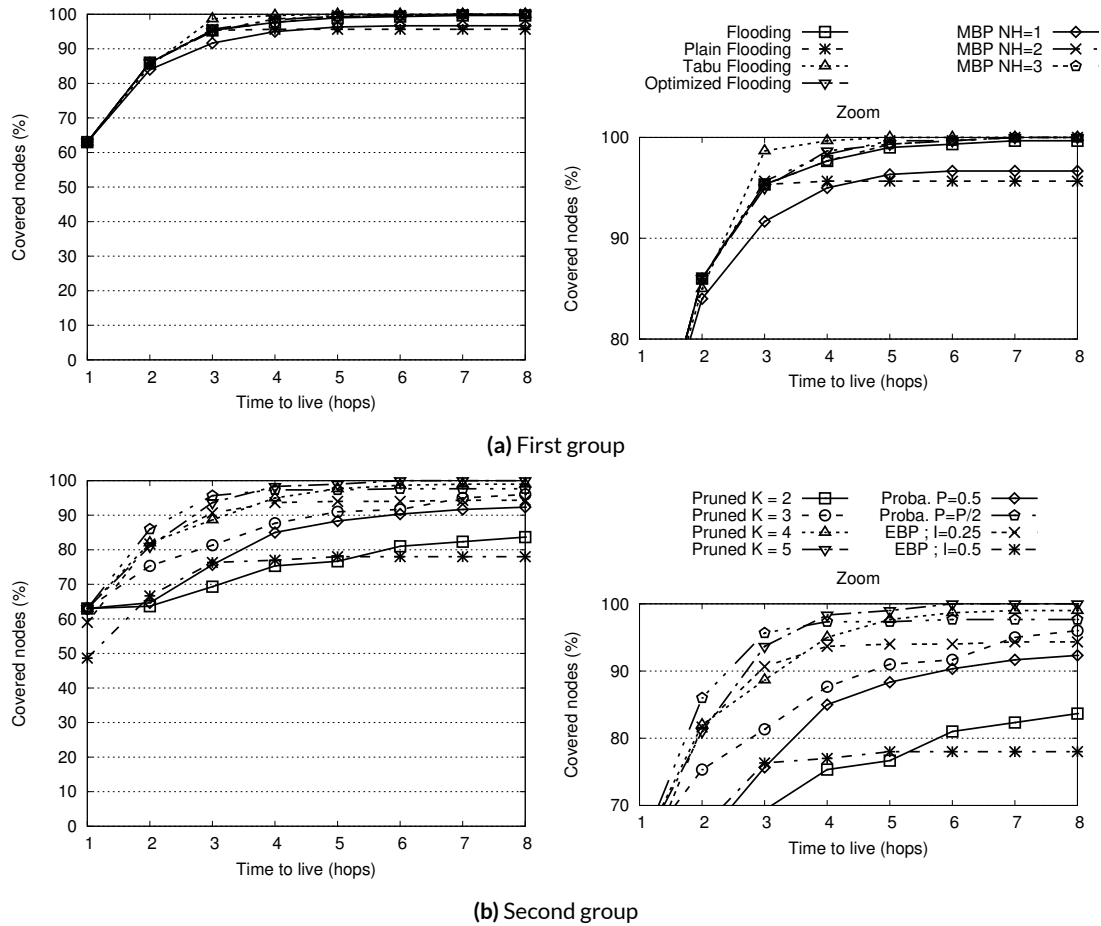


Figure 4.4: Percentage of covered nodes in function of TTL for broadcast protocols in the walking posture

ing from 2 to 5 and shows that with $K = 2$ and $K = 3$ it is almost impossible to cover all the nodes even with higher values of TTL .

Tabu Flooding stands out even for low TTL value (e.g. 3 or 4). Indeed, with *Tabu Flooding*, messages are sent to specific and uncovered nodes. Thus, unlike in most flooding strategies, a node receiving a message will neither consider, nor forward it unless it is among the list of uncovered nodes. With fewer forwarding events, this protocol is able to better sustain low TTL values, at least in an "easy" position such as walking.

The *Probabilistic Flooding* ($P_{new}=P_{old}/2$) strategy shows a good network coverage starting with TTL value equals to 2. Comparing these results with *Probabilistic Flooding* ($P=0.5$), the importance of the first emission of the packet appears clearly. Indeed, with P initially set to 1, this strategy behaves initially as a regular flooding algorithm, with an aggressive diffusion, and then, by dividing P by 2, reduces forwarded message copies, thus limiting the induced load.

For the rest of this work, we chose to set the *TTL* to an initial value of 6 hops, as some strategies are able to reach full network coverage with this value.

4.4.2 PERFORMANCE COMPARISON – SINGLE PACKET BROADCAST

For our first set of evaluations, we chose to examine the scenario on which the gateway only transmits a single broadcast packet. This elementary scenario allows to isolate the protocol behavior without any interaction between successive packets. We compare the different strategies with respect to the following criteria:

- **Network Coverage:** we evaluate the number of nodes that get to deliver the message and present results as the percentage of covered nodes.
- **Latency:** we display the average end-to-end delay from the source to reach its last destination (i.e. the last node successfully covered).
- **Traffic Load:** as a indicator of energy consumption, we evaluate the total number of transmissions and receptions realized by all nodes in the network, assuming that communication is the main source of energy consumption that protocols have an influence on.

Some strategies rely on specific key parameters which have an influence on their performance. To understand these parameters impact, we run simulations with different configurations:

- *MBP*: the threshold on the number of hops NH varies between 1 and 3 hops.
- *EBP*: the inter-hello messages interval, I , varies between $I = 0.25 s$ and $I = 0.5 s$
- *Pruned Flooding*: the number of next hops, K , varies between 2 and 5 nodes.

NETWORK COVERAGE

Figure 4.5 presents the percentage of covered nodes per posture. Looking at these figures, we can clearly distinguish two group of strategies.

The first group, which includes *Tabu Flooding*, *Pruned Flooding* for $K = 5$ and $K = 4$, *Optimized Flooding*, *Flooding* and *MBP* when $NH = 2$ and $NH = 3$, exhibits good performance, close to 100 % coverage in almost all situations. These protocols are able to handle most situations correctly, with the notable exception of the sleep position that turns out to be challenging for these protocols who barely achieve 90 % coverage.

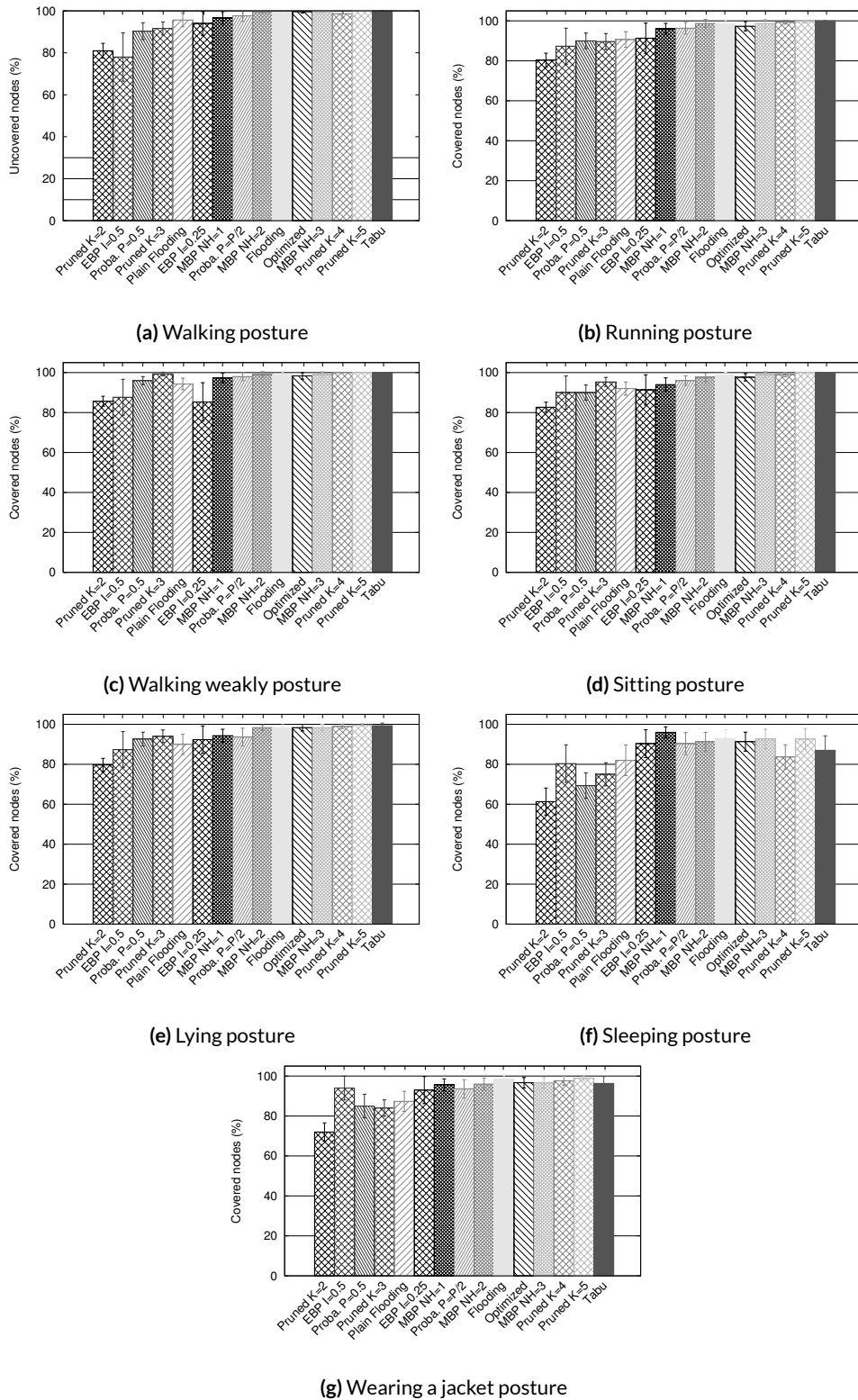


Figure 4.5: Percentage of covered nodes per posture for broadcast protocols

The second group, composed of *Pruned Flooding* for $K = 2$ and $K = 3$, *EBP* for $I = 0.5$, *Plain Flooding* and *Probabilistic Flooding* ($P=0.5$), shows a disappointing performance in all situations. These protocols, or this set of parameters for *Pruned Flooding*, are not suited to this type of network and/or mobility.

In between these two large clusters, protocols like *MBP* for $NH = 1$ or *EBP* for $I = 0.25 s$, or *Probabilistic Flooding* ($P_{new}=P_{old}/2$) have a fair performance, except in the case of the sleep position in which they are, however, more stable than some algorithms belonging to the first group. In the case of *MBP*, messages are delayed and the individual transmission turn out to be well scheduled, reducing collisions and limiting useless forwarding, increasing in turn the chance to reach other nodes. *EBP* is very sensitive to its inter-hello interval. A smaller value ($I = 0.25 s$) induces more load on the network and provoke more collisions than a larger value, but makes it easier to discover the neighborhood and hence allows more transmission attempts.

The performance of *Probabilistic Flooding* ($P_{new}=P_{old}/2$) stresses out the importance of the first transmission of each packet. When compared to *Plain Flooding*, it shows however that it is however not entirely sufficient, as further improvement results from the subsequent transmission attempts.

LATENCY

Figure 4.6 represents the average over all postures of the end-to-end delay, i.e. the time required for the first instance of the message to reach each node. Figure 4.7 shows the average time required to complete the broadcast, i.e. the minimum time to reach every node in the network, per posture.

We can identify in Fig. 4.6 a first group of nodes, composed of the navel, head and upper-arm nodes, which are easy to reach, except for *EBP*. These nodes are the direct neighbors of the gateway node (located on the chest) and the influence of the protocol is marginal in these situations.

EBP needs to acquire and refresh knowledge of the nodes before it takes the decision to transmit a message and waits for the sufficient number of neighbors to be present simultaneously before attempting a transmission. This precaution has a cost in terms of latency which appears in the different postures. We can however notice that for most postures, results are comparable, even in presence of highly variable links. The only really challenging posture is sleep, in which some links are obstructed for long periods, a situation that protocols that wait for enough neighbors to be present cannot handle properly.

Nodes located on the wrist, ankle or thigh are, in most cases, at least two hops away from the source node, which explains the latency increase. For these nodes we can again distinguish

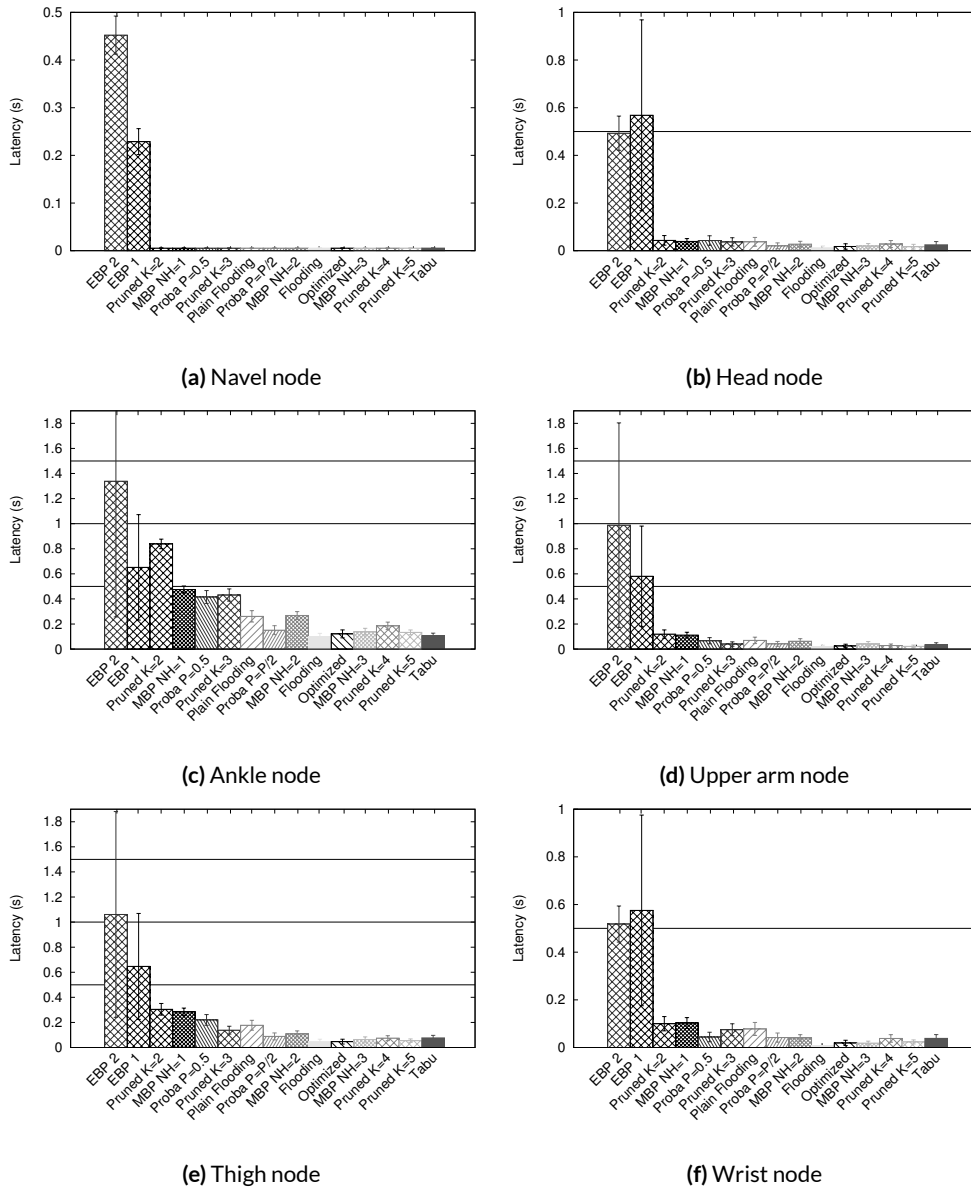


Figure 4.6: Latency per node for broadcast protocols

two groups of strategies: *MBP* when $NH \leq 2$, *Plain Flooding*, *Pruned Flooding* for $K = 2$ or $K = 3$, *EBP* and *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$) generally cause larger delays, while, *MBP* for $NH = 3$, *Optimized Flooding*, *Pruned Flooding* for $K \geq 4$ and *Flooding* exhibit low delays in most situations.

Flooding is the most verbose alternative and always achieves the best performance because nodes broadcast immediately every received packets. *Optimized Flooding* and *MBP* both start

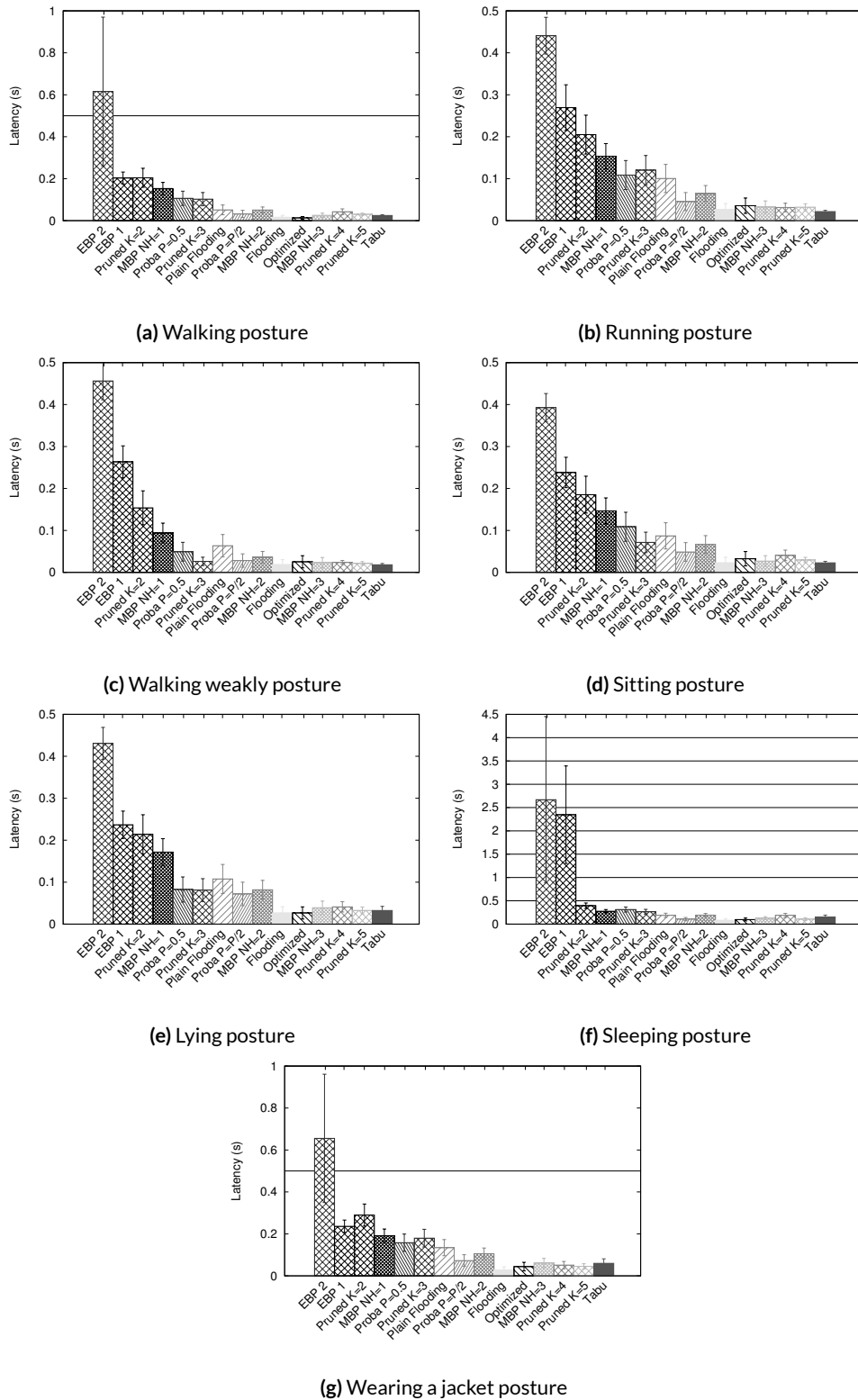


Figure 4.7: Latency per posture for broadcast protocols

the diffusion as *Flooding*, which explains their good performance. *Optimized Flooding* is a bit more adaptable and ultimately reaches a shorter latency than *MBP* because it only eliminates obsolete copies of the messages without impacting the delay. *Pruned Flooding* for $K = 4$ also has a behavior close to *Flooding* due to the network average degree.

Tabu Flooding has a fair performance. As it targets uncovered nodes, these nodes rapidly become a search target for multiple nodes and the probability that they meet one node ready to transmit the packet to them is large.

Probabilistic Flooding ($P_{new}=P_{old}/2$) strategy shows a higher end-to-end delay than *Flooding* due to the decreasing broadcast attempts. But still lower than *Probabilistic Flooding* ($P=0.5$).

EBP performs better in the high mobility postures. Indeed, a peak is noticed in sleep position where some nodes are not in line of sight, sender nodes decide to not broadcast the message and keep it until all conditions are satisfied.

In other hand, *Flooding*, *Optimized Flooding* and *MBP* are the less affected by human body postures. However, we notice better results (closest to *Flooding*) and less variations in function of the postures with *Optimized Flooding* than with *MBP*.

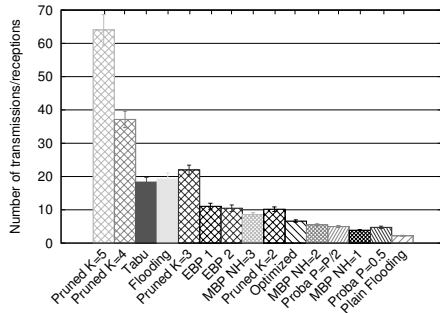
TRAFFIC LOAD

We measured the load induced by the different strategies as the total number of emissions and receptions for each node. This measure, which does not include overhearing not only gives an idea of the wireless channel occupancy, but also of the energy consumption – comparable energy being spent for emission and reception of packets and hence the devices autonomy and their capability to rely on a reduced size battery – and of the level of electromagnetic energy that wearers are exposed to.

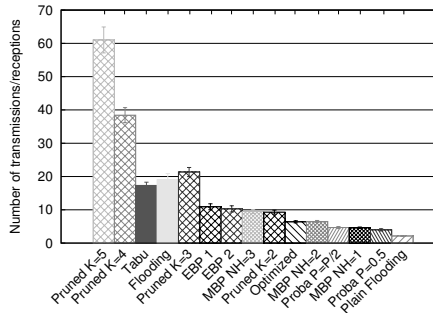
Figure 4.8 compares the total number of emissions and receptions per node for all the studied algorithms and Figure 4.9 shows these figures for each posture. These figures only compare the volume of data packets, leaving aside the control traffic (Hello, acknowledgments, ...)

These figures show, without surprise, that nodes closer to the chest, including the chest itself, are more solicited than peripheral nodes, as they are more natural forwarders and have more active neighbors on average. Comparing the postures, we can notice that most protocols are strongly influenced by the network dynamics, as the number of transmissions increases rapidly with the links variance.

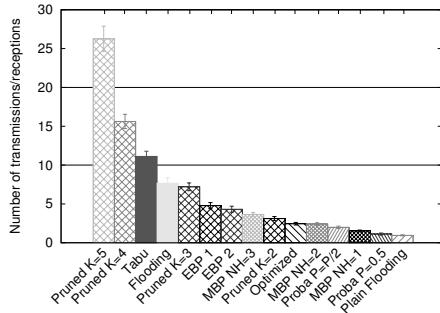
We can categorize once again the different algorithms in three clusters. A first cluster, composed of *Pruned Flooding* for $K \geq 3$, *Tabu Flooding* and *Flooding*, gathers the most verbose protocols. These protocols, trade their good performance in terms of coverage and latency for a high number of transmissions and receptions. With *Flooding*, there is no limitation for nodes on broadcast besides the *TTL*, while *Pruned Flooding* and *Tabu Flooding* even incur more traffic



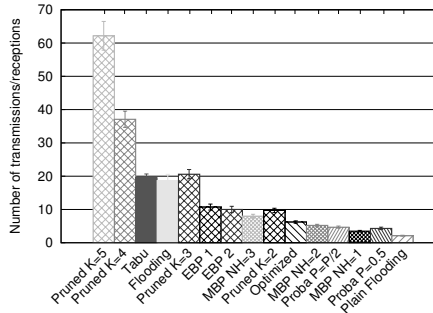
(a) Navel node



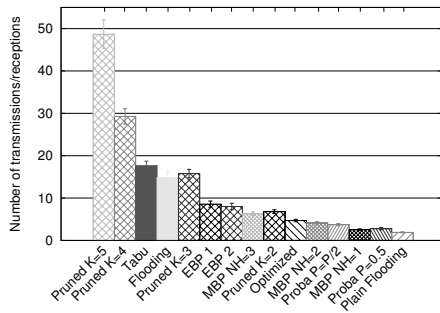
(b) Head node



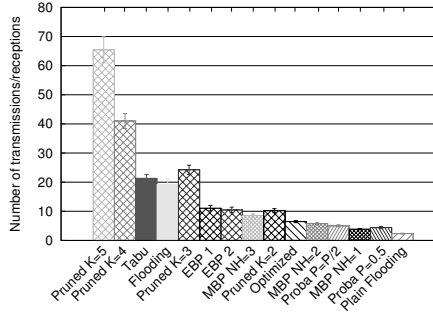
(c) Ankle node



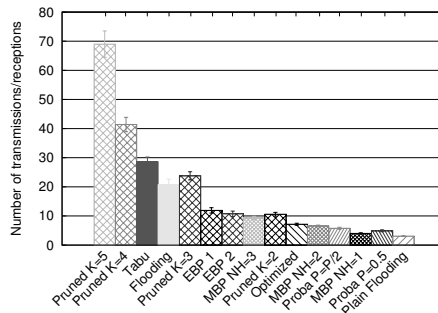
(d) Upper arm node



(e) Thigh node

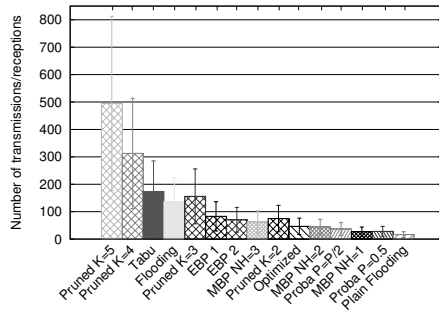


(f) Wrist node

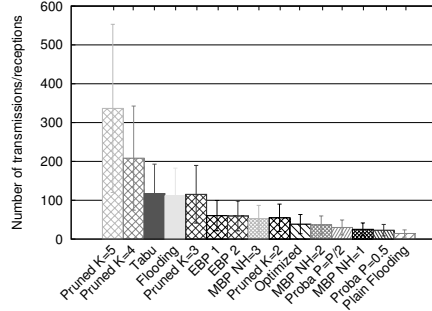


(g) Chest node

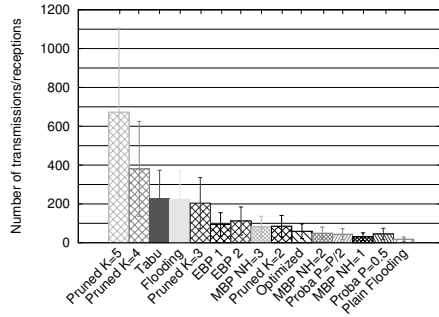
Figure 4.8: Traffic load per node for broadcast protocols



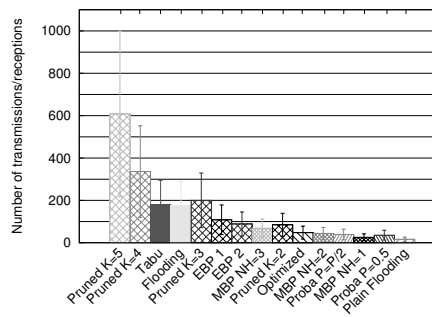
(a) Walking posture



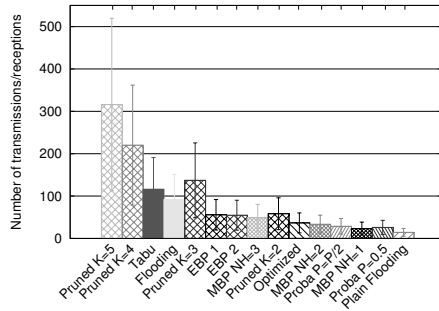
(b) Running posture



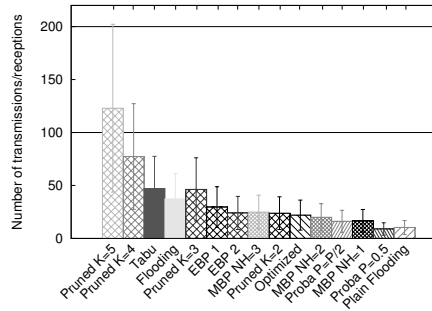
(c) Walking weakly posture



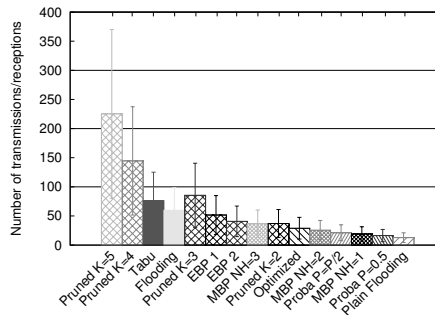
(d) Sitting posture



(e) Lying posture



(f) Sleeping posture



(g) Wearing a jacket posture

Figure 4.9: Traffic load per posture for broadcast protocols

than *Flooding*, as they decompose the broadcast into multiple unicast transmissions to target specific, uncovered or random, nodes. *Pruned Flooding* depends on the parameter K , for example when $K = 3$, each received message generates three copies to be forwarded. For *Pruned Flooding*, while for the end-to-end delay and network coverage, the algorithm performs well with high values of K , in this case a visible decrease in number of transmissions and receptions is observed with lower values of K .

A second group, composed by *Plain Flooding*, *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$), *MBP* for $NH \leq 2$ and *Optimized Flooding*, are usually relatively silent. They require about 3 times less transmissions than *Flooding*, but pay this low traffic volume with a reduced performance, except for *Optimized Flooding* which achieves a good compromise.

Probabilistic Flooding ($P_{new}=P_{old}/2$) performs better than *Flooding* and *Pruned Flooding*. One of the main weaknesses of the flooding algorithms that their performance strongly depends on the *TTL*. Increasing the *TTL* lets the total amount of transmissions and receptions rise very quickly. This issue is partially solved in the adaptive *Probabilistic Flooding* ($P_{new}=P_{old}/2$): the probability decrease works as an automatic brake, drastically reducing the transmission probability. Indeed, the central nodes happen to transmit more than the others nodes on the network, but their neighbors will limit their transmission probability immediately, resulting in a lower number of receptions. This algorithm therefore better distributes the consumption across the network.

Between these two extremes, protocols like *EBP*, *MBP* for $NH = 3$ or *Pruned Flooding* for $K = 2$ generate moderate traffic in most situations.

We notice, for all strategies, the highest number of transmissions and receptions is for *RUN* and *SIT* postures. In fact, *RUN* posture represents the highest mobility posture, even with frequent disconnections, nodes are able to meet more frequent to exchange packets. In *SIT* posture, nodes are close to each other so they are able to exchange packets with a minimum loss.

Sleeping posture presents the lowest number of transmissions and receptions for all strategies. Considering observations related to the percentage of covered nodes (figure 4.5) and to the end-to-end delay (figure 4.7), this low number is related to the permanent disconnections between nodes.

MBP and *Optimized Flooding* strategies are independent from the postures (i.e less variations). Still, *Optimized Flooding* presents a lower number of transmissions and receptions than *MBP* except for some postures which could be explained by the fact that *Optimized Flooding* covers more nodes as shown in figure 4.5.

SUMMARY

Table 4.1 reports the average values for all simulation, all nodes and all postures per protocol for one single packet transmission. We can classify, from these figures, protocols in 4 groups. The first group, containing EPB and *Pruned Flooding* for $K = 2$ and $K = 3$ has disappointing performance. The second group, with MBP (NH = 1), *Probabilistic Flooding* ($P=0.5$) and *Plain Flooding* has a non-satisfying performance but generates little traffic. The third group, containing *Pruned Flooding* ($K = 4$ and 5), *Tabu Flooding* and *Flooding* trades traffic load for performance. Finally, the fourth group, including MBP (NH = 2, NH = 3), *Probabilistic Flooding* ($P_{new}=P_{old}/2$) and *Optimized Flooding* realized a fair compromise between all these aspects.

	Coverage (%)	Latency (ms)	Traffic (pkt)
<i>EBP</i> $I = 0.5 s$	86.3	808.6	64.3
<i>EBP</i> $I = 0.25 s$	91.0	541.9	69.0
<i>Pruned Flooding</i> $K = 2$	77.5	235.2	59.9
MBP NH = 1	95.7	169.5	24
<i>Probabilistic Flooding</i> ($P=0.5$)	87.6	132.3	26.1
<i>Pruned Flooding</i> $K = 3$	89.8	121.0	134.9
<i>Plain Flooding</i>	90.2	104.7	14.7
MBP NH = 2	97.2	85.4	36.0
<i>Pruned Flooding</i> $K = 4$	96.7	59.9	239.9
<i>Probabilistic Flooding</i> ($P_{new}=P_{old}/2$)	95.0	58.1	30.8
MBP NH = 3	97.7	47.9	53.8
<i>Tabu Flooding</i>	97.5	47.6	133.8
<i>Pruned Flooding</i> $K = 5$	98.7	42.5	396.6
<i>Optimized Flooding</i>	97.0	39.3	39.9
<i>Flooding</i>	97.8	31.6	119.2

Table 4.1: Average network coverage, latency and traffic load for all broadcast protocols

4.4.3 PERFORMANCE COMPARISON – INCREASING TRAFFIC LOAD

In this set of simulations, we progressively increase the traffic load to evaluate how protocols react under different traffic conditions. When the load increases, packets may either be dropped before being emitted due to a full MAC-level queue, or get emitted but be lost to some receivers because of collisions and congestion may prevent some nodes to access the medium. In all cases, some packets will never reach their destination, or be received through alternate, usually longer, paths, which may disrupt the packets reception order.

In this section, we gradually increase the packets load from 2 packets/s to 1000 packets/s. Each packet is 544 bits long and the medium capacity is 250 kbit/s. If the resulting load becomes clearly unrealistic with respect to classical WBAN applications, it allows us to characterize the global behavior and to detect tripping points. The MAC buffer size is set to 100 packets.

We evaluate the different algorithms with respect to the following criteria:

- **Packet Reception Ratio (PRR)**: presents the average number of received messages per node presented as the percentage of received messages.
- **Drop causes**: we aim to identify the number of dropped packets and drop causes (due to collisions or busy channel).
- **Volume of unnecessary traffic load**: reports the average number of redundant copies of each packet received by each node.
- **Packets sequencing**: represents the percentage of packets that manage to reach the different nodes in the network, but after a subsequent packet has already been received.

We show network-wide average values as well as node-per-node values to have an accurate evaluation.

An additional evaluation of MAC buffer size impact is also presented in the sequel.

PACKET RECEPTION RATIO (PRR)

Figure 4.10 presents the average proportion of received packets over all packets, when the emission throughput increases. This measure allows us to see how reliable the different protocols are under different loads.

We can notice that all protocols have the same behavior: starting from a few packets per second, which depends on the protocol (5 for *MBP* and *Flooding*; 10 for *Optimized Flooding* and *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$)) and on the posture, the percentage decreases rapidly to converge to similar values, around 10%. The protocols classification is similar for all postures: *Plain Flooding* and *Optimized Flooding* resist slightly better, followed by *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$). The *Pruned Flooding* and *Flooding* strategies have the worst scalability. This classification follows the different approaches verbosity: the protocols that tend to let numerous copies of the same packet travel in the network have lower scalability when compared to more cautious protocols. There is no real effect of the posture on the general behavior of the different protocols, however the initial performance and the tripping point are different in function of the nodes relative mobility.

Table 4.2 reports the number of packets successfully received by all the nodes in the different postures for different protocols in the scenario where the source emits a saturating throughput

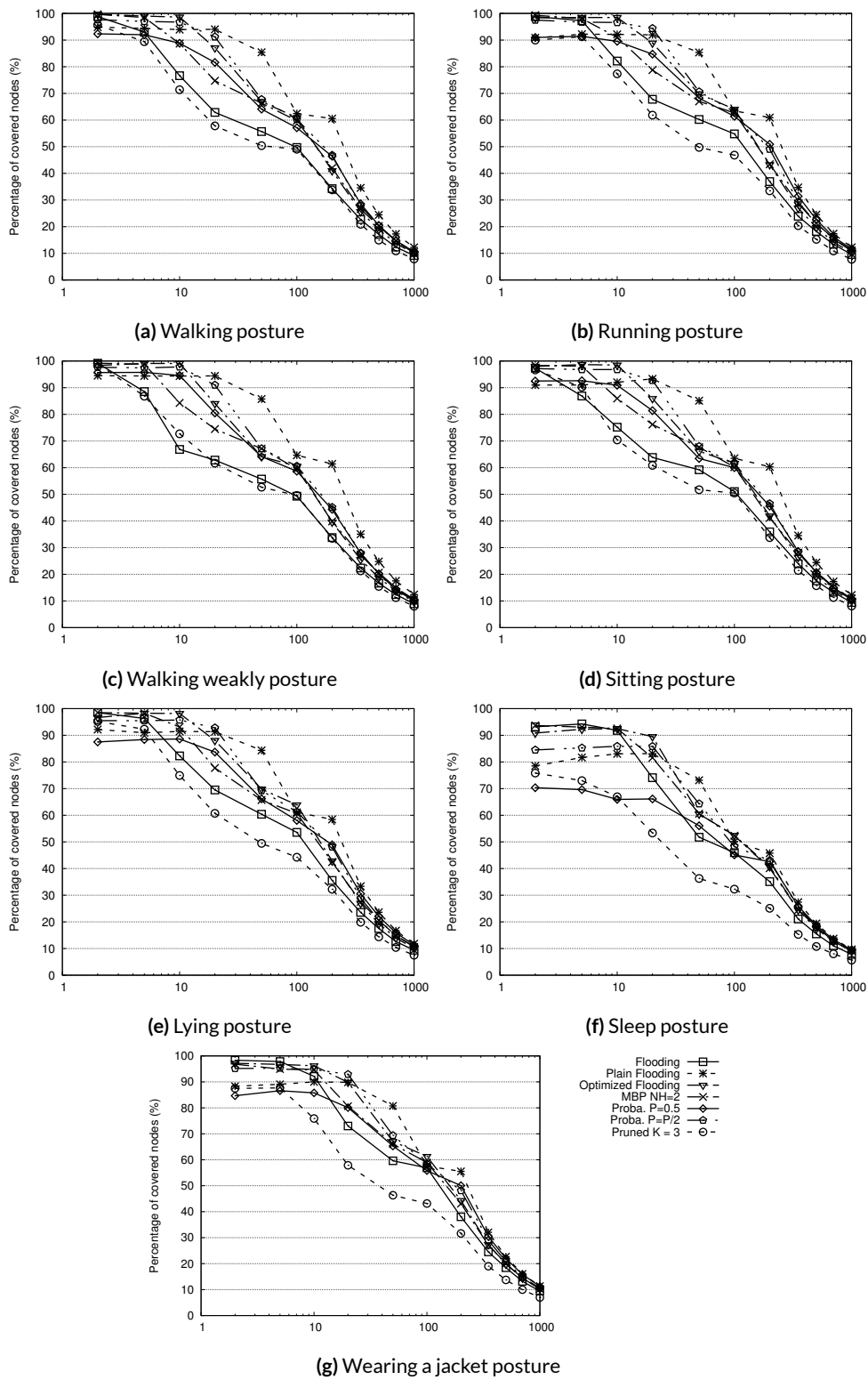


Figure 4.10: Packet reception ratio (PRR) per posture for all broadcast protocols

of 1000 packets/s. We let emitter generate 10000 packets, most of which are dropped in the sender's queue, as the wireless channel cannot sustain such a load. Figures reported in the table are the average over 50 simulations for each scenario.

	Flooding	MBP	Optimized	Plain	Probabilistic ($P=0.5$)	Probabilistic ($P_{new}=P_{old}/2$)	Pruned	Tabu	Average
Walking	274	268	359	408	263	358	250	223	300.4
Running	271	263	309	336	247	310	251	216	275.4
Weakly	291	301	373	420	275	381	328	264	329.1
Sitting	298	261	355	352	246	361	268	223	295.5
Lying	270	256	311	326	251	303	250	234	275.1
Sleeping	166	175	203	174	95	200	100	108	152.6
Wearing	252	198	277	253	194	278	215	182	231.1
Average	260.3	246	312.4	324.1	224.4	313	237.4	207.1	

Table 4.2: Number of successfully received packets in function of the posture – saturated scenario

These figures confirm that sleeping is, by far, the most challenging position for the different protocols, followed by wearing jacket. Concerning protocols, *Flooding*, *MBP*, *Pruned Flooding*, *Probabilistic Flooding ($P=0.5$)* and *Tabu Flooding* have lower success rates than *Plain Flooding*, *Probabilistic Flooding ($P_{new}=P_{old}/2$)* and *Optimized Flooding*. This indicates that neither the too verbose solutions nor the ones that rely on neighbors identification deal correctly with a high load, which is logical as both families generate a high data or control traffic. Indeed, the good ranking of *Plain Flooding* even suggests that a single transmission from all nodes is sufficient in most positions, except for Sleep where *Optimized Flooding* behaves slightly better.

Table 4.3 reports the number of distinct packets received by each node, averaged over 50 simulations and over all positions, truncated to 1 digit.

The value for chest represents the number of packets that are received back from neighbors forwarding and may does not have any application-level meaning. This confirms that the most difficult nodes to reach are the ones located at least two hops away from the source (Ankle and thigh). Here we can see that *Plain Flooding* is the most efficient protocol when it comes

	Flooding	MBP	Optimized	Plain	Probabilistic (P=0.5)	Probabilistic ($P_{new}=P_{old}/2$)	Pruned	Tabu	Average
Navel	602.4	670	626.1	786.7	818.7	674.4	596.7	583.4	669.8
Chest	449.4	439.1	507.8	642.1	474.4	559.1	511.2	468.7	506.5
Head	514.5	645.8	547.5	716	704	597	531.2	514.7	596.3
Up. Arm	445.5	503.1	492.8	645.4	590.8	533.4	480.7	448	517.5
Ankle	326.5	333.7	382.8	442.4	305	395	301.1	258.2	343.1
Thigh	375.2	391.7	443.2	561.5	463	472.7	417.4	371.4	437.0
Wrist	431.8	482.5	485.8	652.4	605.1	530.7	481.1	440	513.7
Average	449.3	495.1	498	635.2	565.8	537.4	474.2	440.6	

Table 4.3: Number of successfully received packets per node – saturated scenario ; all postures average

to reaching these "difficult" nodes, followed by *Probabilistic Flooding* ($P_{new}=P_{old}/2$) and *Optimized Flooding*.

DROP CAUSES

Table 4.4 reports the number of dropped packets due to collisions and busy channel (drop before sending) per posture.

And table 4.5 reports the same figure per node, averaged over the postures.

First, it is worth noting that collisions and medium load evolve together, which is expected on a single channel. Comparing protocols, these results are coherent with the other statistics: verbose protocols such as *Flooding*, *Tabu Flooding*, *Pruned Flooding* and *MBP* are more prone to increase the medium load. *Plain Flooding* and *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$), on the opposite, have a lighter impact on the channel occupancy, while *Optimized Flooding* generates a quite high load. Concerning positions, the amount of collision is lower in positions whose success rate is low, which indicates that the success rate is more related to reachability of the nodes than to an excessive collisions amount.

When breaking down the drops per node, even if we can see variations among the nodes, the volume of collisions and packets dropped after failing to access the channel remains relatively uniform across the network. We can notice that central nodes suffer from relatively low

		Flooding	MBP	Optimized	Plain	Probabilistic (P=0.5)	Probabilistic ($P_{new}=P_{old}/2$)	Pruned	Tabu	Average
Walking	Collisions	965.6	808.6	748.1	471.1	455.6	628.4	774.2	750.7	700.3
	Busy channel	56.5	38.5	43.0	17.0	19.8	33.6	46.5	41.6	37.1
Running	Collisions	950.0	865.7	716.6	476.1	412.9	608.5	806.4	830.0	708.3
	Busy channel	43.5	29.2	31.9	12.6	11.7	23.6	37.9	35.6	28.3
Weakly	Collisions	1048.5	858.4	832.6	495.4	537.3	684.9	898.4	870.2	778.2
	Busy channel	64.1	45.9	51.0	19.9	27.5	40.0	56.2	50.6	44.4
Sitting	Collisions	859.8	762.9	702.0	424.6	434.7	586.6	738.0	720.4	653.6
	Busy channel	54.0	38.9	44.4	16.5	22.5	35.5	47.7	42.2	37.7
Lying	Collisions	897.2	812.9	682.5	461.2	395.4	587.2	777.5	808.9	677.8
	Busy channel	38.8	24.5	28.1	11.5	11.0	21.5	35.5	33.3	25.5
Sleeping	Collisions	632.0	683.0	535.5	422.2	287.0	487.9	674.2	763.8	560.7
	Busy channel	15.9	14.4	9.6	4.4	3.1	7.4	14.8	19.4	11.1
Wearing	Collisions	878.6	794.5	696.3	499.2	389.6	612.3	777.4	888.5	692.1
	Busy channel	27.2	17.7	20.7	9.6	6.7	16.0	26.0	29.5	19.2
Average	Collisions	890.3	798.0	701.9	464.3	416.1	599.4	778.0	804.6	
	Busy channel	42.9	29.9	32.7	13.1	14.6	25.4	37.8	36.1	

Table 4.4: Drop causes per posture for all broadcast protocols

collisions level even if they are relatively more prone to suffer from a busy channel. This can be explained by the fact that that these nodes act more often as emitters than the others. The wrist node appears to be suffering from both effects, while the ankle node appears more isolated. The head, upper arm have different but average profiles.

UNNECESSARY TRAFFIC LOAD

Table 4.6 reports the average number of redundant copies of each packet received by each node.

These figures are the average over 50 simulations and over all postures. We can see that nodes which are direct neighbors of the source, such as the navel, but also the chest, head and upper arm, are more exposed than the others. These figures are somehow coherent with the successful packets ratio presented in Table 4.3, which seems to indicate that the nodes seeing

		Flooding	MBP	Optimized	Plain	Probabilistic (P=0.5)	Probabilistic ($P_{new}=P_{old}/2$)	Pruned	Tabu	Average
Navel	Collisions	834.9	681.1	635.3	390.4	358.0	528.5	695.9	728.2	606.5
	Busy channel	50.7	35.0	40.6	17.9	19.9	31.8	46.1	42.2	35.5
Chest	Collisions	840.5	732.9	644.5	369.9	317.2	527.3	747.3	823.9	625.4
	Busy channel	57.7	36.6	46.0	13.8	20.3	35.1	53.6	45.3	38.5
Head	Collisions	800.9	859.7	634.6	425.3	393.6	549.1	697.7	707.1	633.5
	Busy channel	45.8	26.7	35.7	15.3	15.8	27.4	41.2	38.5	30.8
Up. Arm	Collisions	939.1	767.2	742.6	516.5	454.1	645.5	798.7	817.3	710.1
	Busy channel	51.9	36.4	38.8	15.9	17.5	30.2	44.5	44.0	34.9
Ankle	Collisions	767.4	827.9	611.0	389.0	388.8	515.5	726.1	696.4	615.3
	Busy channel	5.2	3.4	3.4	1.7	1.5	2.8	3.5	5.0	3.3
Thigh	Collisions	988.8	852.5	808.8	575.3	501.7	706.1	881.2	909.5	778.0
	Busy channel	29.5	28.1	20.4	8.9	8.2	16.5	23.8	26.5	20.2
Wrist	Collisions	1060.2	864.6	836.8	583.5	499.2	723.9	899.3	950.0	802.2
	Busy channel	59.3	42.9	43.7	18.1	19.1	33.8	52.0	50.8	40.0
Average	Collisions	890.3	798.0	701.9	464.3	416.1	599.4	778.0	804.6	
	Busy channel	42.9	29.9	32.7	13.1	14.6	25.4	37.8	36.1	

Table 4.5: Drop causes per node for all broadcast protocols

the most traffic are also the better covered ones, yet the figures for the chest node, for instance, or the head node do not follow this pattern. Chest ranks 5th in terms of coverage but 2nd in terms of redundant receptions, while head and, to a smaller extent, wrist are often covered and only experience moderate redundant receptions.

When it comes to protocols comparison, we can conform our previous conclusions: *Flooding* and *Tabu Flooding* are very verbose followed by *MBP* and *Pruned Flooding*, while *Plain Flooding* and *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$) are the most silent alternatives. *Optimized Flooding* scores fairly. Compared to the one single packet scenario, we can notice that *Tabu Flooding* used to have a good performance in terms of traffic load and now scales poorly due to the decomposition of the broadcast into multiple unicast transmissions.

	Flooding	MBP	Optimized	Plain	Probabilistic (P=0.5)	Probabilistic ($P_{new}=P_{old}/2$)	Pruned	Tabu	Average
Navel	92.7	4.2	26.2	6.2	19.7	15	29.1	92.5	35.7
Chest	51.2	8	5.7	3.7	4.7	3.8	48.5	23.8	18.7
Head	24.2	20.4	20.7	3.5	7.4	6.5	18	17	14.7
Up. Arm	29.2	30	9.2	2.1	14.7	7.1	21.4	34.2	18.5
Ankle	7	26.2	9	4	1.1	2.7	7.8	21.5	9.9
Thigh	19	29.7	5.1	1.4	4.1	2.2	6.1	23.4	11.4
Wrist	14	16.4	8.2	3.8	5.7	7.2	17.5	29	12.7
Average	33.9	19.3	12.0	3.5	8.2	6.4	21.2	34.5	

Table 4.6: Number of redundant receptions per node – saturated scenario ; all postures average

PACKETS SEQUENCING

Figure 4.11 presents the average per node of the proportion of de-sequenced packets, i.e. packets that manage to reach the different nodes in the network, but after a subsequent packet has already been received.

In all cases, we can notice three phases: first the different protocols start experiencing out-of-order packets at a proportion that increases from 5 to 10 packets per seconds, depending on the protocol to about 100 packets per second. Then the de-sequencing proportion starts to decrease as the collisions, drops and MAC delays make the overall reception ratio decrease.

The maximum proportion of out-of-sequence packets remains low, though, around 10% at the maximum. *Probabilistic Flooding* ($P=0.5$ or $P_{new}=P_{old}/2$), *Plain Flooding* and *Pruned Flooding* approaches usually have the lowest proportion of de-sequenced packets and the latest tipping point, while *MBP* and *Flooding* generally stand on the other end of the panorama. *Optimized Flooding* has an intermediate performance, with a late tipping point followed by a fast increase to a relatively low maximum value.

These results are coherent with the observations on the coverage probability: as the channel load increases, protocols performance starts to decrease, which rules out the most verbose solutions rapidly. *Pruned Flooding* has a low de-sequencing proportion because of its low coverage.

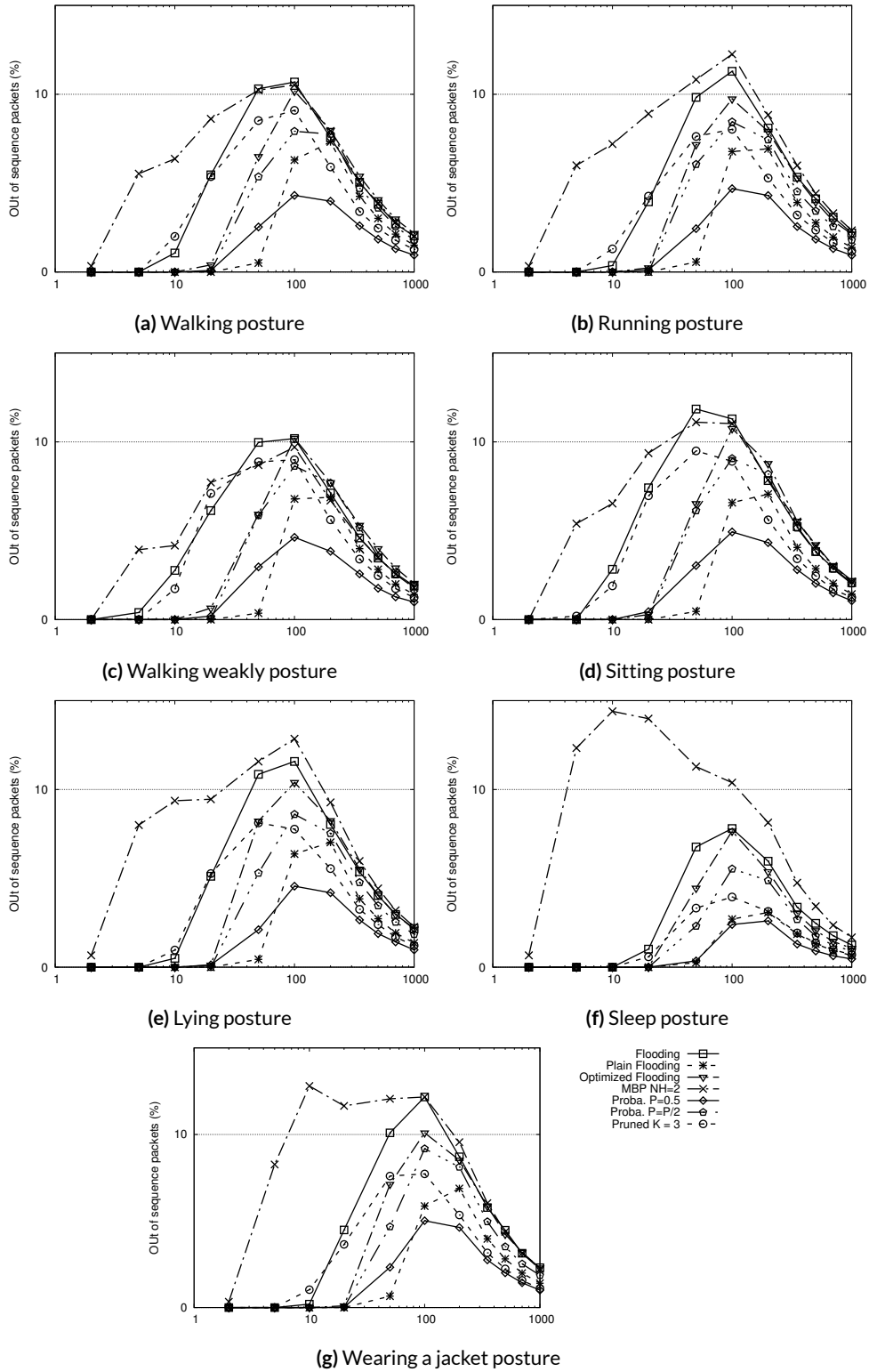


Figure 4.11: Percentage of de-sequencing per posture for broadcast protocols

4.5 CONCLUSION & FUTURE WORKS

In this chapter, we evaluated through simulations the performance of several DTN-inspired broadcast strategies in a WBAN context. Our simulations, realized with the Omnet++ simulator, the Mixim framework and a WBAN channel model, allowed us to compare 9 strategies. The simulations were realized over a 7 nodes mobile network that includes a dense area, as well as distant nodes in 7 types of movements. We were able to characterize the compromise that exists between the capacity to flood the whole network quickly and the cost induced by this performance. Our results show that the most complex strategies that require control traffic, or to maintain complex states are not necessarily the most effective. Simple strategies like *Probabilistic Flooding* ($P=0.5$ or $P_{new} = P_{old}/2$), which adapt a probability to forward the packet to the distance traveled in the network, or even *Plain Flooding* which never re-forwards a packet already received have a good performance, especially at higher loads. Some strategies, like *Tabu Flooding* which targets only uncovered nodes, or *Pruned Flooding* which forwards packets to a limited number of random neighbors achieve good results when the load is low (one packet) but scale very poorly.

We also propose and evaluate our own adaptive algorithms. *MBP* [28], for Mixed Broadcast Protocol that applies a more aggressive strategy in the center of the network, where connections are more stable, and becomes more cautious at the border of the network, where a blind transmission has a good chance of success. Although this strategy is very efficient when properly tuned in a low load scenario, its scalability is not satisfactory. Yet, it represents a very good candidate for low traffic networks. *Optimized Flooding* improves the performances of *MBP* by relying on information embedded in the packets and information stored in each forwarder. This strategy shows a promising performance and scales well, which encourages us to realize further studies, including experimentation on a real network.

A future work would be a detailed study of existing channel models [214] and a comparison with the current channel model. Furthermore, another interesting future direction would be to consider collisions among multiple WBANs [91, 108].

5

Cross Layer Approach in WBAN

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5.1 INTRODUCTION

Layer cooperation in cross-layer based schemes enhances the overall WBAN performance. For instance in a cross layer scheme, the QoS requirements at application layer can be communicated to the MAC layer in order to achieve better resource allocation. Furthermore, the channel state information and battery level could be communicated to the network layer to avoid paths including low reliable links.

The current work extends in several ways the results in chapter 4 that were published in [28, 30], where we evaluate in multi-hop WBAN several broadcast strategies.

We propose a *network-MAC cross-layer broadcast protocol*, called *CLPB: Cross Layer Protocol for Broadcast*, designed for multi-hop topologies and resilient to realistic human body mobility.

CLPB is optimized to exploit the human body mobility by carefully choosing the most reliable communication paths (i.e paths with the highest success transmission probability) in each studied posture. Moreover, our protocol includes a slot assignment mechanism that reduces the energy consumption, collisions, idle listening and overhearing. Additionally, *CLPB* includes a light synchronization scheme that helps nodes to resynchronize with the *Sink* node on the fly.

Our protocol outperforms existing flat broadcast strategies in terms of network coverage, latency, traffic load and correct reception of FIFO-ordered packets (i.e. packets are received in the order of their sending). Furthermore, our protocol maintains its good performances up to 190Kb/s transmission rates.

This chapter is organized as follow: section 5.2 presents relevant works on cross layer approaches in WBAN. In section 5.3, we detail *CLPB*, our new cross-layer broadcast protocol, functioning. In section 5.4, we extensively evaluate protocols in [28, 30] and our new cross layer protocol. Section 5.5 concludes the chapter.

5.2 RELATED WORK

Several works have discussed cross layer principle in different networks WSN [88, 16, 110], DTN [216], adhoc [12, 178, 128].

In [88], authors exploit knowledge about specific MAC layer parameters of the energy-aware MAC protocol WiseMAC to the routing layer of WSN in order to achieve low latency. While in [110], authors present a framework for cross-layer design towards energy-efficient communication characterized by a synergy between the physical and the medium access control (MAC) layers.

In [16], a unified cross-layer protocol is developed, which replaces the entire traditional layered protocol architecture that has been used so far in WSN.

In order to address the trade-off between link utilization and energy efficiency, authors in [216] develop a cross-layer data delivery protocol for Delay/Fault Tolerant-Mobile Sensor Network (DFT-MSN). Due to the characteristics of DFT-MSN, the communication links exist only with certain probabilities due to sparse network density and sensor node mobility. In addition, sensor nodes have very limited battery power. First, the sender contacts its neighbors to identify a set of appropriate receivers. Then, the sender gains channel control and multicasts its data message to the receivers. Furthermore, authors provide solutions to reduce the collision probability and to balance between link utilization.

5.2.1 CROSS-LAYER IN WBAN

There are very few cross-layered protocols specifically designed for WBAN [117, 204, 46]. The proposed WBAN cross-layer approaches prove that there is still a need for further optimization of such networks and that cross-layering is efficient to accomplish that.

In the following we will discuss mainly multi-hop cross-layer protocols that involve MAC and Network layers and take advantages of the characteristics and parameters of the medium access layer to implement efficient routing protocols.

Adaptive Multi-hop tree-based routing (AMR), proposed in [152] is a distributed spanning-tree based approach which considers battery level, Received Signal Strength Indicator (RSSI) and number of hops. AMR balances energy consumption amongst nodes by which it provides extended network lifetime and an efficient number of transmissions per delivered packet. However, it does not take into account the mobility of the human-body.

In [56], Elhadj *et al.* present a Node Management Entity (NME) and a Hub Management Entity (HME) architectures based on IEEE 802.15.6 standard. The two architectures combine cross and modular design architecture to ensure network reliability and enhance the WBAN Quality of Service (QoS). Although authors have treated data heterogeneity, their proposals which are based on IEEE 802.15.6 standard suffer from high energy consumption due to idle listening.

Lahlou *et al.* present EEAWD [113], a MAC-Network cross layer energy optimization model for WBAN. EEAWD was introduced to cope with EAWD [59] limitations that do not take into account the medium access control and physical layer specifications. With EEAWD, authors introduce two traffic classes (normal and emergency), and consider a pseudo mobility model. Authors only focused on energy efficiency parameter despite others.

In [36], Braem *et al.* propose WASP: Wireless Autonomous Spanning tree Protocol, a converge-cast cross-layer protocol for multi-hop wireless body area networks. WASP is a slotted protocol that uses a spanning tree for medium access coordination and traffic routing. Each node will tell its children in which slot they can send their data using a special packet called WASP-scheme.

Each node has a unique WASP-scheme constructed based on its parent scheme. WASP-scheme is also used as acknowledgement to each node's parent and as resources request if needed. However, for some parent nodes sleep period is shorter because they have to handle more children than other parent nodes. In addition, latency is correlated to the number of levels of the spanning tree. WASP is not resilient to realistic human body mobility due to parent-child definition, parent forward data packet from its child only. Scalability is also an issue since each node has only one packet to send per cycle and increasing number of nodes decreases throughput. In [68], authors implement WASP and discuss results.

Latré *et al.* propose CICADA [115] as an improvement of WASP. CICADA sets up a network tree in a distributed manner. CICADA aims to reduce energy consumption with the use of a spanning tree and an assignment of transmission slots to ensure collision free medium access. A cycle is divided into a control sub-cycle (used for schemes transferring) and a data sub-cycle. Each sub-cycle has its own scheme for slot allocation. These two schemes are both sent in the control sub-cycle. When all nodes have received schemes from their parents, the control sub-cycle ends and the data sub-cycle starts. In addition, CICADA handles network nodes joining. To remedy the delay issue with WASP protocol, in CICADA, nodes at the bottom of the tree start sending and all nodes send data to the *Sink* node in one cycle. CICADA has not been evaluated against realistic human body mobility and various transmission rates. Moreover, the medium access control scheme proposed in CICADA is specifically designed to handle converge-cast. Its adaptation to broadcast was reported as open question. A secure version of CICADA is presented in [186, 187].

In [227], authors formalize the maximization of converge-cast energy efficiency with respect to its MAC and routing as resource constrained optimization problem. The maximization problem is linear with two MAC protocols: S-MAC (locally synchronized wakeup) and O-MAC (locally staggered wakeup). Authors propose MeeCast a centralized algorithm that solves the maximization problem with linear programming techniques. They assumed a low and uniform traffic, reliable communication and no interference. Authors compare it to Dozer and show that MeeCast assume a constant energy consumption rate whether sending or receiving.

In [9] and [26], authors present a Cross-layer Opportunistic MAC/Routing (COMR) protocol for multi-hop WBAN but the evaluation was made using a static network topology. As an extension, in this work the performance of COMR protocol is investigated taking into account node's mobility with different speeds depending on body positions. The impacts of varying payload sizes are evaluated for both COMR and Simple Opportunistic Routing (SOR) protocols using a mobility model in two scenarios: standing and walking.

Nadeem *et al.* introduce SIMPLE – Stable Increasing-throughput Multi-hop Protocol for Link Efficiency in WBAN [148]. A cost function is used to select the parent node with high

residual energy and minimal distance to the *Sink* node. The system model considers sensor nodes with equal power and computational capabilities. The *Sink* node broadcasts a packet which contains its position while the other nodes broadcast a packet which contains their ID, position and energy status. Then, *Sink* node computes the cost function of each node based on the received information from the hello packet. The cost function is transmitted to all nodes and only nodes with minimum cost function are selected as forwarder. This selection is processed for each round. Finally, forwarder nodes assign TDMA schedule to other nodes hence nodes with data to transmit wake up only in their assigned time slot.

In [69], Garudadri *et al.* propose a cross-layer scheme based on application and MAC layer interactions. They focus on treating the issues of end-to-end packet losses due to link deterioration, interference, congestion and system load. The packet loss mitigation approach is based on the emerging signal processing concept, the compressed sensing, wherein significantly few sensor measurements can be used to recover signals with arbitrarily fine resolution. Lost packets are identified at the application layer via a sequence number field in the packet header of the lower layers. However, authors have not considered neither traffic heterogeneity nor node synchronization.

In [48], Davaslioglu *et al.* presents CLOEE – Cross-Layer Optimization for Energy Efficiency to determine the PHY and MAC layer parameters: optimal payload size (frame length) and number of pulses. Authors study IEEE 802.15.6 ultra-wideband (UWB) that use impulse radio (IR). CLOEE optimizes resource allocation for energy efficiency and throughput.

Ben Elhadj *et al.* present a cross-layer based data dissemination algorithm for IEEE 802.15.6 [57]. Authors considered a two-hop extended star topology since their work is based on IEEE 802.15.6 standard. Authors adopt a simple reverse tree route discovering approach rooted at the coordinator for a two-hop topology network using hello beacons exchange. The coordinator (i.e *Sink* node) starts with a beacon broadcast. Beacon messages are then forwarded only once by all sensors. Each node that received one or more beacons will choose a next hop to the coordinator based on the shortest path in terms of delay. In addition, authors introduce data traffic priorities and a pre-emptive queuing model at a WBAN node. However, high priority packets can contend resources and low priority packets can be blocked at the MAC buffer. To cope with this problem authors define the maximum time that a packet can wait in the buffer. Latency stills an issue.

An extended work of [57] was presented in [58], authors present a Priority-based Cross Layer Routing Protocol (PCLRP) along with a Priority-based Cross layer Medium Access Channel (PCLMAC) for healthcare applications. PCLRP is an adaptive protocol regarding the slot assignment technique. It combines TDMA and priority guaranteed CSMA/CA approaches to access the channel and defines a synchronization scheme to avoid collisions, data loss and idle listening and face topology changes. PCLRP defines three traffic classes: General

monitoring packets, delay sensitive packets and emergency packets, while, PCLMAC operates in compliance with the defined traffic category. PCLRP incorporates an interaction between the application, MAC, network and physical layer. Indeed, the MAC slot allocation is customized for the underlying routing protocol taking into account the QoS requirements of the healthcare application and physical parameters. PCLRP exploits the exchanged MAC frames to build the routing scheme without a route discovery message exchange. Moreover, the routing algorithm exploits node's battery level and the MAC frame structure (TDMA number of slots) in the relay selection process.

Note that cross-layer approach showed a good compromise between reliability, energy efficiency, QoS requirements, etc. However, proposed protocols, discussed earlier, focus only *converge-cast* (multiple source nodes send packets to a unique destination *Sink*). To the best of our knowledge we have, no paper has discussed broadcast in WBAN exploiting a cross-layer approach. In addition, these proposals handle body mobility by reconstructing and updating the tree topology used for packet routing.

In our work, we consider an homogeneous traffic where all sensed data are considered with the same priority level and requires 100% reliability. Considering data different level of priority is an interesting approach but only for specific applications.

5.3 CLPB: CROSS LAYER PROTOCOL FOR BROADCAST IN WBAN

In this section, we introduce our new cross layer broadcast protocol *CLPB*.

CLPB handles both the control medium access and the broadcast process. *CLPB* is a slotted protocol that builds on top of a pruned communication graphs constructed based on the channel model [89] described in section 2.7.2.

Sink node broadcasts packets in the network addressed to all nodes along different body part. The ultimate goal is to ensure that all nodes receive all packets in the shortest delay possible and with the least energy consumption. Our protocol takes into account number of packets to be broadcasted and their transmission frequency.

In order to include the channel model specificities in the broadcast process, *CLPB* needs a *preprocessing* phase. The preprocessing phase is only handled at the beginning and only at the *Sink* node level.

After this preprocessing phase, *Sink* broadcasts packets that will carry both data and control information (e.g. slots assignment, synchronization information, etc).

We settled on a centralized preprocessing phase conducted on the *Sink* node. It is more efficient to handle the preprocessing phase centralized in one unique node since our work addresses small scale networks (up to 10 nodes). A distributed preprocessing phase using for example control message exchange would have heavy costs especially given human body mo-

bility. In addition, a distributed preprocessing phase would be more interesting in a large scale network. Also, we target medical critical applications where WBAN network is precisely inspected by medical staff, nodes position is carefully selected according to the desired application.

5.3.1 PREPROCESSING PHASE

The aim of preprocessing phase is to identify, for each posture and for each node N_i , one or more reliable paths from *Sink* node to N_i , i.e paths with the highest success transmission probability.

This phase is executed only by *Sink* node before starting the broadcast process. The final allocation result will be included on the subsequent packets.

The mobility model, we are using, gives us signal attenuation between each couple of nodes for different postures as the average attenuation (in dB) and the standard deviation (in dBm). We involve these channel characteristics in our protocol design.

First, *Sink* node computes, based on the mean attenuation and the standard deviation of each link between a couple of nodes, the Cumulative Distribution Function (CDF) of the random attenuation $x : F(X) = P[x < X]$ where X is a threshold. X represents the maximum acceptable attenuation referring to the transmission power -55 dBm and the reception sensibility -100 dBm . X is equal $(-55 - (-100))=45 \text{ dBm}$ and $F(45)$ represents the probability of a successful transmission at this link. A similar approach is used by the authors of [37].

Then *Sink* computes a pruned communication graph. Nodes in this graph are the nodes in the network, the edges correspond to the links with success transmission probability greater than 0.5.

Figure 5.1 shows the 7 pruned communication graphs, one for each posture, obtained by applying the procedure described above.

Note that at the end of the preprocessing the obtained communication graphs are not necessary trees. In the following we will denote these communication graphs G_j where j is the number of the corresponding posture.

Then, *Sink* selects a set of *senders*, for each posture, starting from top to down (from node at the head to node at the ankle). A sender is a node that presents a link with a high transmission success probability with a node other than the *Sink*.

For each node, N_i , in the communication graph G_j , *Sink* computes the paths between *Sink* and N_i with maximal reliability. The set of nodes on these paths are included in the *senders* set for the graph G_j .

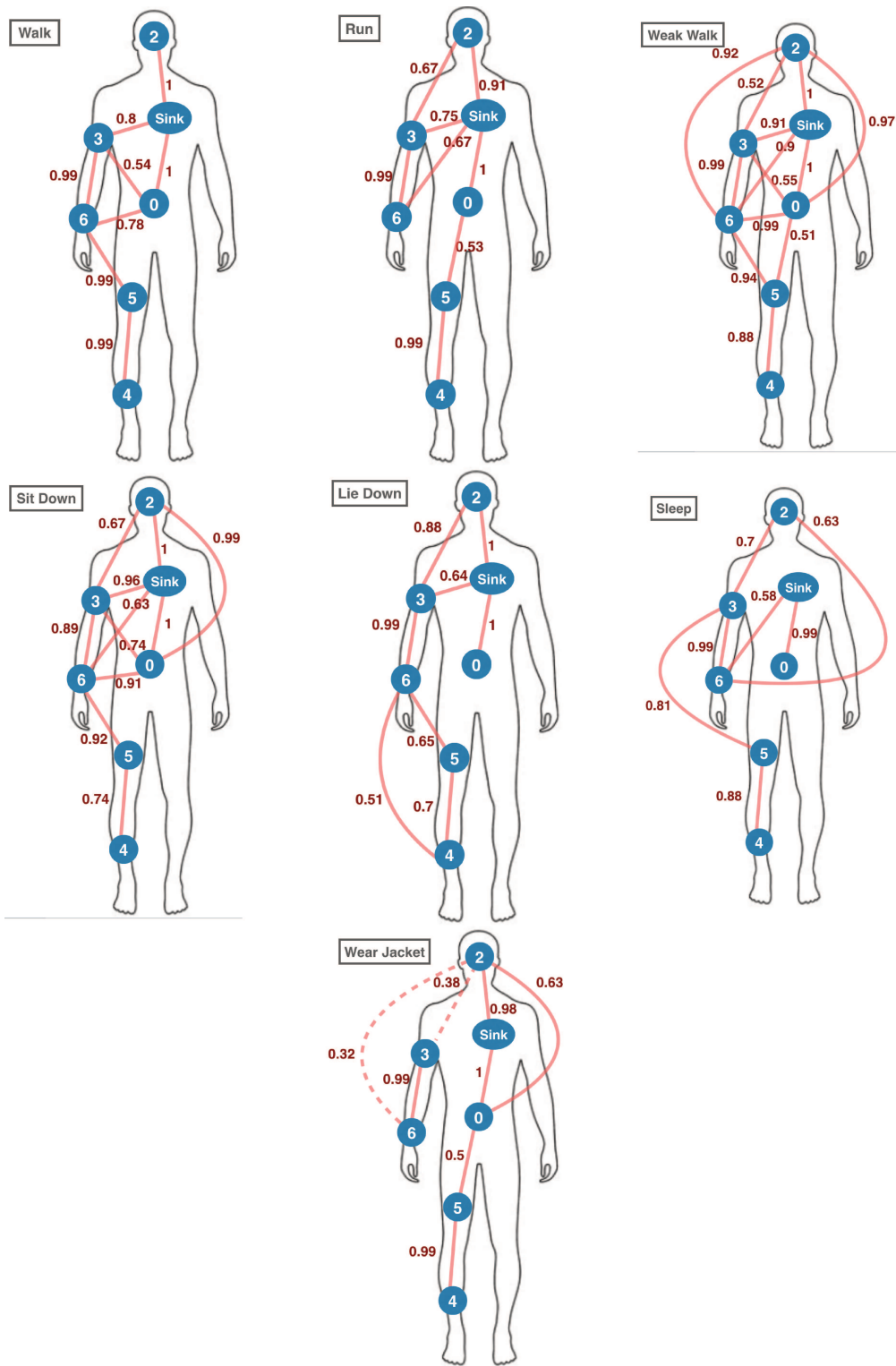


Figure 5.1: The resulting communication graphs (a graph per posture) on which CLPB is based

We suppose that *Sink* node knows in advance the postures of the body. Postures detection is out of the scope of our study. Note that several works [130, 119, 221, 67] addressed the posture detection.

SENDERS SELECTION Sink starts with the set of directly (one-hop) connected nodes, stored from top to down (storage is based on node position on human body i.e top refers to node on the head, down refers to the node on the ankle). The order of senders is important to increase reliability and transmission success.

Note S_1 is the set of directly connected nodes to the *Sink* node and $n_{1i} \in S_1$.

$\forall n_{1i} \in S_1$ be S_2 the set of directly (one-hop) connected nodes to n_{1i} and $n_{2i} \in S_2$.

n_{1i} is selected as a sender only if $S_2 \neq \emptyset$ and $n_{2i} \notin S_1$.

5.3.2 CLPB PROTOCOL OVERVIEW

After the preprocessing phase, *Sink* assigns a slot to each sender outputted by the preprocessing phase (see section 5.3.1). A node is allowed to forward previously received packets only if it is a sender and the current slot was assigned to it.

Then, *Sink* node broadcasts packets which include data and a *medium access and synchronization scheme*. The broadcasted packets will carry both data and control information (e.g. slots assignment, synchronization information, etc).

Note that with our protocol, no control packets exchange is needed and CLPB uses data packets to control both medium access and broadcast.

Our protocol assumes that nodes execute in synchronized time-slots. Furthermore, it is assumed that the boundaries of slots are also synchronized.

5.3.3 MEDIUM ACCESS AND SYNCHRONIZATION SCHEME

Sink node divides time into *cycles*. A cycle corresponds to a fixed number of time slots i.e. a sequence of time slots equals to the number of senders, in other words, equals to the number of nodes allowed to broadcast including *Sink* node.

In a cycle, during its corresponding time slot, each sender node is allowed to forward data received in the previous time slot or previous cycle.

Cycle duration is given by the following equation eq.5.1:

$$CycleDuration = NumberOfSenders * SlotDuration \quad (5.1)$$

Nodes synchronize with *Sink* node via the scheduling and synchronization scheme described in details in the sequel.

Our new cross layer approach minimizes coordination overhead. No exchange of control packets is needed because informations added to data packets are used as control informations and thus nodes are aware of communication and traffic characteristics.

We also show that nodes are able to resynchronize even though some packets are lost.

That is, each received packet is considered as a reference for the current time slot. A *sender* includes in packets it forwards its slot number called *current slot* and the next cycle starts in a way that at the reception of this data packet, nodes can position the current time with respect to the current slot and to the next cycle.

Figure 5.2 presents the synchronization and scheduling parameters detailed below.

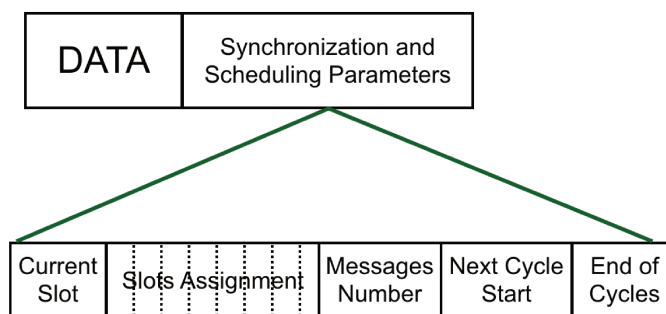


Figure 5.2: CLPB packet description (data & synchronization and scheduling parameters)

1. **Current slot:** is a reference slot that allows nodes to position in time.
 For example in Figure 5.4, *Sink* node sends the packet with a current slot equals to 0. Suppose, node 3 misses the packet reception from *Sink* node while node 0 receives it correctly. Node 0 broadcasts the packet with a current slot equal to its time slot (i.e. 2). Node 3 receives the packet, it checks slot scheduling, it is a sender but its time slot (equal to 1) is less than the current time slot (equal to 2) so it will not broadcast the packet at this cycle and it will schedule the transmission for the next cycle.
2. **Slots Assignment:** is the result of the preprocessing phase. It describes what time slot did the *Sink* node assigns to each sender. Slot number 0 is always assigned to *Sink* node. Based on example Figure 5.4, node 3 broadcasts at time slot 1 then node 0 at time slot 2, while nodes 2 and 4 are not designated as senders.
3. **Messages Number:** represents the total number of packets to be sent by *Sink* node and that should be received by all nodes. This parameter enable nodes to recognize missing packets.

4. **Next Cycle Start:** Depends on the transmission rate of *Sink* node. This transmission rate allows to compute the time between two consecutive cycles: the *CyclesInterleave* parameter presented below.

$$CyclesInterleave = \quad (5.2)$$

$$\begin{cases} 0, & \text{if } Sink \text{ Transmission rate} < \text{Cycle Duration} \\ (\lceil Transmissionrate/SlotDuration \rceil) & \\ *SlotDuration - CycleDuration(eq.5.1), & \\ \text{otherwise.} & \end{cases} \quad (5.3)$$

If the transmission rate is such that *Sink* node receives an application packet while previous packet is still in broadcast (the current cycle is not finished), then *CyclesInterleave* is null. As shown in the example **a**) in Figure 5.3, *Sink* node receives an application packet every 2 time slots, which is less than a cycle duration (5 time slots). In this case, *Sink* node puts packets in its buffer and waits the end of the current cycle. Then, it immediately starts a new cycle.

If *Sink* node receives an application packet much later. For example, as shown in the example **b**) in Figure 5.3, *Sink* node receives an application packet every 8 time slots, which is greater than a cycle duration (5 time slots). Hence, packets are queued at MAC layer if the total input rate exceeds the packet forwarding rate at the MAC layer. In this case, nodes enter in a sleep mode waiting for the next cycle.

Next Cycle Start is a key parameter that optimizes nodes duty cycle. In fact, instead of alternating between reception and sleep mode each time slot, nodes will go back to sleep and schedule wake up when more packets are available.

5. **End of Cycles:** Nodes sleep definitely based on *End of Cycles* value.

Nodes have to wake up each cycle in order to receive data packets. However, in case of packet loss, nodes will keep waiting for lost packets. To avoid such scenario, *Sink* node computes, based on traffic parameter, an end of communication time that we call *End of Cycles*. Then, when a node reaches the estimated time, it decides to sleep definitely (an another alternative could be chosen regarding the application requirements specified by the concerned entity: a come back to the initial state i.e half of the slot awake the other half sleep, or a wakeup after x seconds, etc.)

Slots Scheduling	0	1	2	3	4
Senders	Sink	3	0	6	5

Msg i: Application message i for the sink

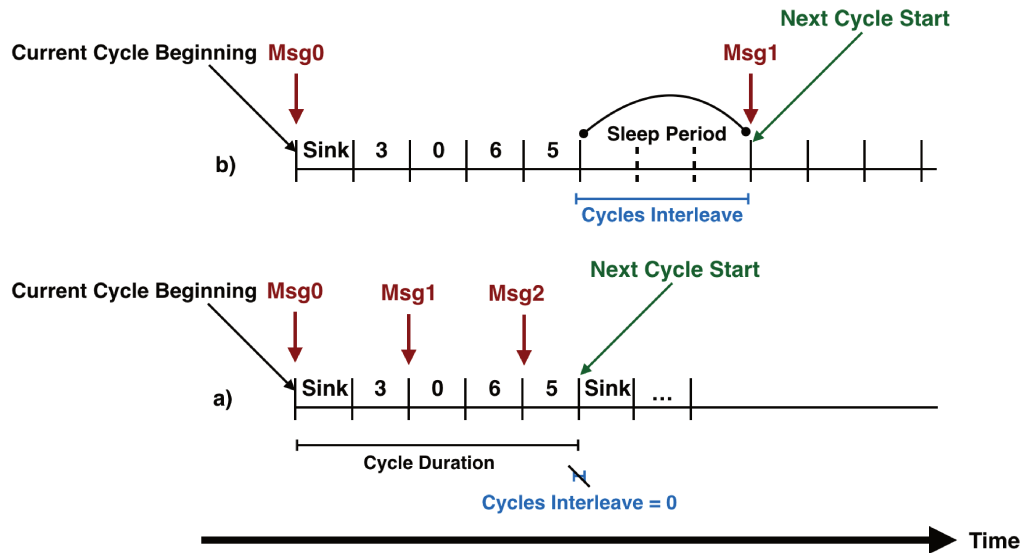


Figure 5.3: Cycles interleave based on CLPB protocol. Both cases: a) High transmission rate & b) Low transmission rate

Nodes recognize missing packets scenario by comparing the number of received packets with the number of messages defined in the synchronization parameter (Figure 5.2).

To avoid that nodes miss data packet, it is important to over estimate *End of Cycles* parameter by supposing the worst case given by the Equation 5.4 below. We suppose that, in worst case, a sender has to delay broadcast to its time slot at the next cycle to send each packet. This gives as:

$$EndOfCycles = MessagesNumber * CycleDuration(eq.5.1). \quad (5.4)$$

NUMERICAL EXAMPLE Suppose *Sink* node application requires to broadcast 10 packets per second.

After pre-processing phase, 5 senders including *Sink* node are allowed to broadcast. With a slot duration equals to 5ms, then, cycle duration (equation 5.1) is equal to 25ms.

If we suppose that each of the 10 packets have to wait for the next cycle to be broadcasted, then, End Of Cycles (equation 5.4) is equal to $10 * 25 = 250$ ms.

5.3.4 PROTOCOL DETAILS DESCRIPTION

Figure 5.4 resumes a simple broadcast scenario with our new cross layer protocol.

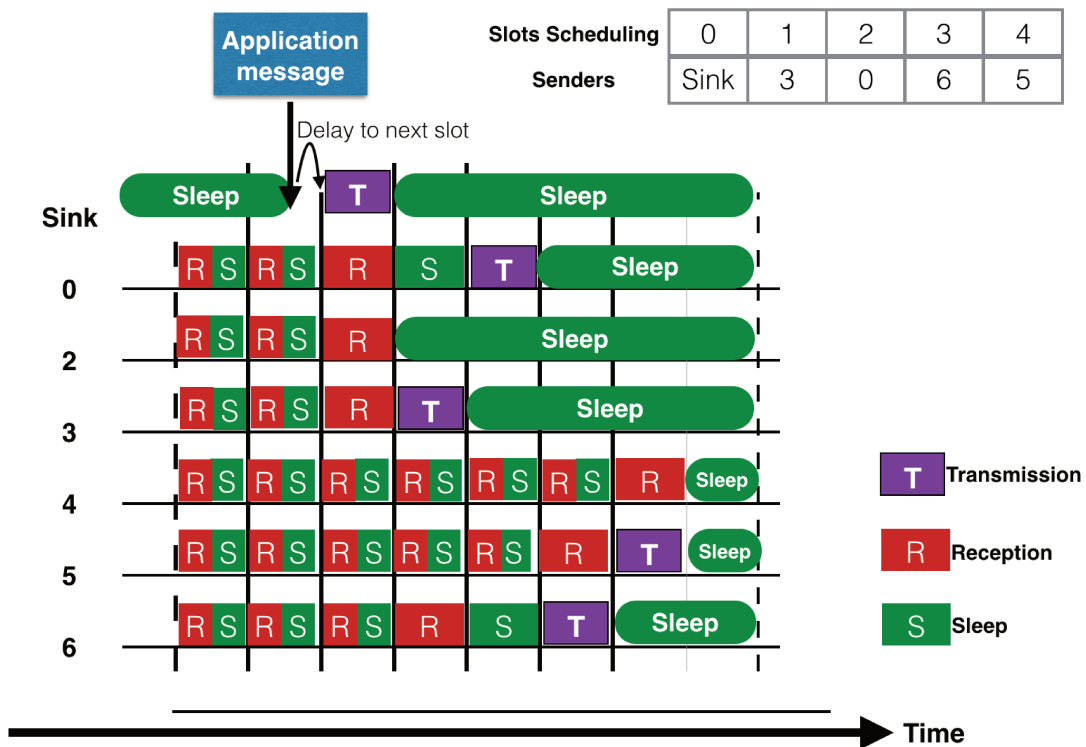


Figure 5.4: CLPB execution for posture walking with only one packet broadcasting from *Sink* node to all nodes in the network

Upon reception of an application packet, *Sink* node schedules the broadcast of the packet plus the medium access control scheme information (see section 5.3.3) at the next time slot.

Each *sender* node wakes up on each slot on reception mode, RX, for a period of time that equals to a half time slot. During this period, there are two possible cases:

- no packet is received: The node goes back to sleep mode and wakes up (on reception mode RX) next time slot.

- a packet is received:
 - if it is allowed to transmit (based on time slots schedule), then it schedules a transmission.
 - if more packets are expected, based on *Sink* node transmission rate, then it computes the next cycle and goes back to sleep at the end of the current cycle. Otherwise, it sleeps definitely.

When a node wakes up on its assigned time slot to transmit previously received data, it transmits until the end of its slot. After this point, it delays the remaining packets to be broadcasted in the next cycle.

Nodes alternate between: reception, sleep and transmission modes. However, differently from other similar techniques, we strive to reduce the number of state switches and the duty cycle duration.

As shown in Figure 5.4, after receiving a packet, nodes 0 and 6 sleep waiting their turn to broadcast based on the scheduling scheme. Also, node 3 sleeps after broadcasting the packet. Leaf nodes, nodes 2 and 4, sleep after receiving all packets while sender nodes sleep after transmitting all received packets.

Note that in this example, we suppose only one packet is broadcasted in the network so nodes sleep after receiving the unique packet. If more than one packet is expected, nodes sleep at the end of the current cycle and wake up the next cycle.

In the following, we present CLPB algorithm 4.

CLPB implements the following primitives:

- $\text{SendUp}(m)$: Each node sends up m to the network level upon receiving m .
- $\text{Broadcast}(m)$: All sender nodes perform a broadcast of the message m in the network during their time slot.

V : Set of all nodes in the network; Node $i \in V$

5.4 PERFORMANCE ANALYSIS

In this section, we compare flat broadcast strategies studied in chapter 4 and published in [28] (and its companion technical report [30]) and the new cross layer protocol *CLPB*.

In chapter 4, we adapted, implemented and compared 9 multi-hop broadcast strategies [28, 30] with different levels of knowledge and extensively evaluate them against realistic human body mobility in a scenario that is representative of a real WBAN.

The following is a recall of the considered broadcast strategies:

Algorithm 4 CLPB algorithm

```
1: procedure WAITING FOR MAC MESSAGE( $m$ ) ▷  $\forall i \in V$  and  $i \neq Sinknode$ 
2:   repeat(Each time slot)
3:     while !TimeOut do
4:        $macState \leftarrow RX$ 
5:     end while
6:      $macState \leftarrow SLEEP$ 
7:   until A message is received
8: end procedure
9: procedure UPON RECEIVING APPLICATION MESSAGE( $m$ ) ▷ Only for Sink node
10:   $macState \leftarrow TX$ 
11:  Communication graphs construction ▷ Paragraph 5.3.1
12:  Synchronization and scheduling parameters computation ▷ Paragraph 5.3.3
13:  Buffering  $m$  ▷ Time is divided into time slots and msg broadcasting is scheduled at
    the next time slot
14:  Schedule Broadcast( $m$ ) at the next time slot
15:   $macState \leftarrow SLEEP$ 
16: end procedure
17: procedure UPON RECEIVING MAC MESSAGE( $m$ ) ▷  $\forall i \in V$  and  $i \neq Sinknode$ 
18:  SendUp( $m$ )
19:  if  $i \in Senders$  then
20:    Buffering  $m$ 
21:    if  $currentSlot < MyTimeSlot$  then
22:      Schedule Broadcast( $m$ ) at MyTimeSlot
23:    else
24:      Schedule Broadcast( $m$ ) at NextCycle
25:    end if
26:  end if
27:  if  $MessagesReceived < MessagesToWait$  then
28:    Schedule SLEEP End of this cycle
29:    Schedule WakeUp at NextCycle
30:  else
31:     $macState \leftarrow SLEEP$ 
32:  end if
33: end procedure
```

- Flooding In *Flooding* strategy nodes rebroadcast each received packet as long as its TTL is greater than 1, decreasing its TTL value by 1 unit every time.
- Plain Flooding *Plain flooding* is more restrictive: using sequence number, a received

packet is delivered to the application layer and rebroadcasted only once. Other copies are discarded.

- Pruned Flooding Each node forwards a received packet to K neighbors, chosen randomly, according to uniform distribution. We run simulations with different K values.
- Probabilistic flooding ($P=0.5$) Nodes decide to broadcast packets according to a constant probability, P . For our simulations, we chose $P = 0.5$.
- Probabilistic flooding ($P_{\text{new}} = P_{\text{old}}/2$) Nodes decide to broadcast according to a probability P that is divided by 2 every time a packet is broadcasted. In our simulations, the initial forwarding probability is set to 1.
- MBP: Mixed Broadcast Protocol Proposed in [28], this strategy is a mix between the *dissemination-based* and *knowledge-based* approaches. The broadcast begins as a basic flooding algorithm (i.e *Flooding* strategy). When a node receives a message, it checks the number of hops NH this message has traveled since its emission by the *Sink*, either stored as an explicit value, or based on the TTL, and compares it to a threshold, Δ . As a result, nodes choose either to broadcast to its neighbors in range, to wait for acknowledgements or to acknowledge. This algorithm depends on two main parameters to continue or stop the broadcast: Δ , the threshold on the number of hops traveled so far and Q , the number of expected acknowledgments. Both parameters have an influence on the algorithm performance that we evaluated through simulation. Concerning Q , we determined that the best performance was achieved with different values according to node position: for example, for non natural forwarder nodes like head and ankle nodes, Q should be set to 0. In section 5.4, we show results for Δ equals to 1, 2 and 3.
- OptFlood: Optimized Flooding This protocol was proposed in [30]. It builds up on classical flooding, which exhibits excellent performance in terms of network coverage and completion delay, while attempting to keep the number of transmissions and receptions low to preserve energy and channel resources. OptFlood maintains, associated to each packet, two counters: *cptGlobal*, embedded into the packet itself (or in all its copies) and every time the packet is received by a node that had not received it previously, the node increases this counter value to reflect the fact that the packet reached a new node, and *CptLocal*, which is a per-packet variable local to each node and it is a local copy of the maximum value of *cptGlobal* that the node has seen so far.

The evaluation focuses the scenario where a specific node in the network, the *Sink*, sends a single packet to all the nodes in the network.

Our evaluation targets the parameters below:

- **Reliability: Percentage of covered nodes** Note that *Sink* node is our unique source of packets. We therefore compute the number of nodes that have received the message and present results as the percentage of covered nodes.
- **FIFO Order: Percentage of de-sequencing** The percentage of packets received in a different order than the sending order. This parameter is evaluated only in the case when *Sink* transmission rate is greater than $1\text{packet}/s$.
- **Latency: End to end delay:** The average delay a packet takes to reach a node. For QoS, the latency in critical medical applications should be less than $125ms$ [57].
- **Traffic load:** as an indicator of energy consumption which is a main concern in WBAN. Energy consumption is presented as the number of transmissions and receptions.

Section 5.4.2 presents simulation results when strategies are stressed with a *Sink* node transmission rates from 2 to 1000 packets/s.

The goal of studying strategies performance with various transmission rates and different MAC buffer sizes is to highlight the hidden impact of some parameters like MAC buffer size on strategies performances. Our simulation confirms that a cross-layer approach offers the best performance.

Section 5.4.3 focuses the case when *Sink* node broadcasts only 1 packet. The results confirm that even for low rates, the cross-layer approach offers the best performance.

5.4.1 SIMULATION SETTINGS

We use the discrete event simulator Omnet++ [212] and the Mixim framework [109] enriched with the described channel and mobility model in section 2.7.2.

Above the channel model, we used standard protocol implementations provided by the Mixim framework [109]. In particular, we used, for the medium access control layer, the IEEE 802.15.4 implementation (2006 version, non-beacon mode). Sensitivity levels, packets header length and other basic information and parameters are based on IEEE 802.15.4 standard.

Each data point is the average of 50 simulations run with different seeds. We used Omnet++ default internal random number generator, i.e. the Mersenne Twister implementation (cMersenneTwister; MT19937) for the uniform distribution, with different initialization seeds for each run, and the normal distribution generator (cNormal) for the signal attenuation.

The transmission power is set at the minimum limit level -55 dBm [30] that ensures a limited energy consumption, reduces wearers electromagnetic exposition and allows an intermittent communication given the channel attenuation and the receiver sensitivity -100 dBm .

For CLPB protocol, slot duration is set to $5ms$ with a bitrate equal to $1Mb/s$.

5.4.2 INCREASING TRANSMISSION RATE

BROADCAST RATES UP TO 1000 PACKETS/S – MAC BUFFER SIZE 100

In this section, we stress the different strategies with *Sink* node transmission rate up to 1000 packets/s and a MAC buffer size equals to 100 which is the default value in the IEEE 802.15.4 standard.

In all body postures, *CLPB* strategy outperforms the flat strategies. Moreover, *CLPB* good performance is maintained up to 200 packets/s while the other strategies percentage drops starting from 10 packets/s.

NETWORK COVERAGE Figure 5.5 presents the percentage of covered nodes in function of *Sink* transmission rate. This rate is presented as the number of broadcasted packets per second.

All flat broadcast strategies behave similarly: Going to 1000 packets/s, the percentage of covered nodes almost linearly decreases to reach 10%. At 100 packets/s, only 50% of the network is covered.

With *Flooding* strategy, the percentage decreases starting from 5 packets/s. With this strategy, nodes broadcast each received packet without restrictions. In the network the important amount of packets overloads the network and creates collisions.

For *Pruned Flooding* and *MBP*, the percentage decreases starting from 5 packets/s too. With *Pruned Flooding*, even if nodes are restricted to broadcast to only K nodes, still, with $K = 3$ many packets copies are generated and the network is overloaded. Also, because of the random choice of the next hops, some nodes are not qualified for forwarding. With *MBP*, broadcast is only delayed to give time for the other nodes to receive and acknowledge correct reception. This delay allows *MBP* to avoid network overloading and hence limits collisions and ensures a better percentage of covered nodes than *Flooding* and *Pruned Flooding* strategies.

In sleeping posture, *Flooding* and *MBP* strategies are able to maintain a good percentage of covered nodes equal to 91% up to 10 packets/s. Due to low mobility and less available links, network is less overloaded so less collisions and less packets loss. However, in more mobile and dense postures, performance decreases, for example, in running posture, *Flooding* strategy shows 82% of covered nodes for 10 packets/s and 75% in sitting posture.

CLPB maintains a good percentage, greater than 90%, up to 350 packets/s. Indeed, with 350 packets/s, *Sink* has one packet to send each 0.00285s. In our settings, a cycle lasts 5 time slots with a time slot duration equals to 5ms. At the end of the cycle, *Sink* node has 8 packets waiting in buffer for broadcast. Or, with a bit rate equals to 1Mbps, *Sink* node can send up to 5Kbs during its time slot. A packet size is equal to 544 bits then *Sink* node can send up to (5Kbs/544 bits) packets i.e 9 packets per time slot. Beyond the rate 350 packets/s, performance falls to

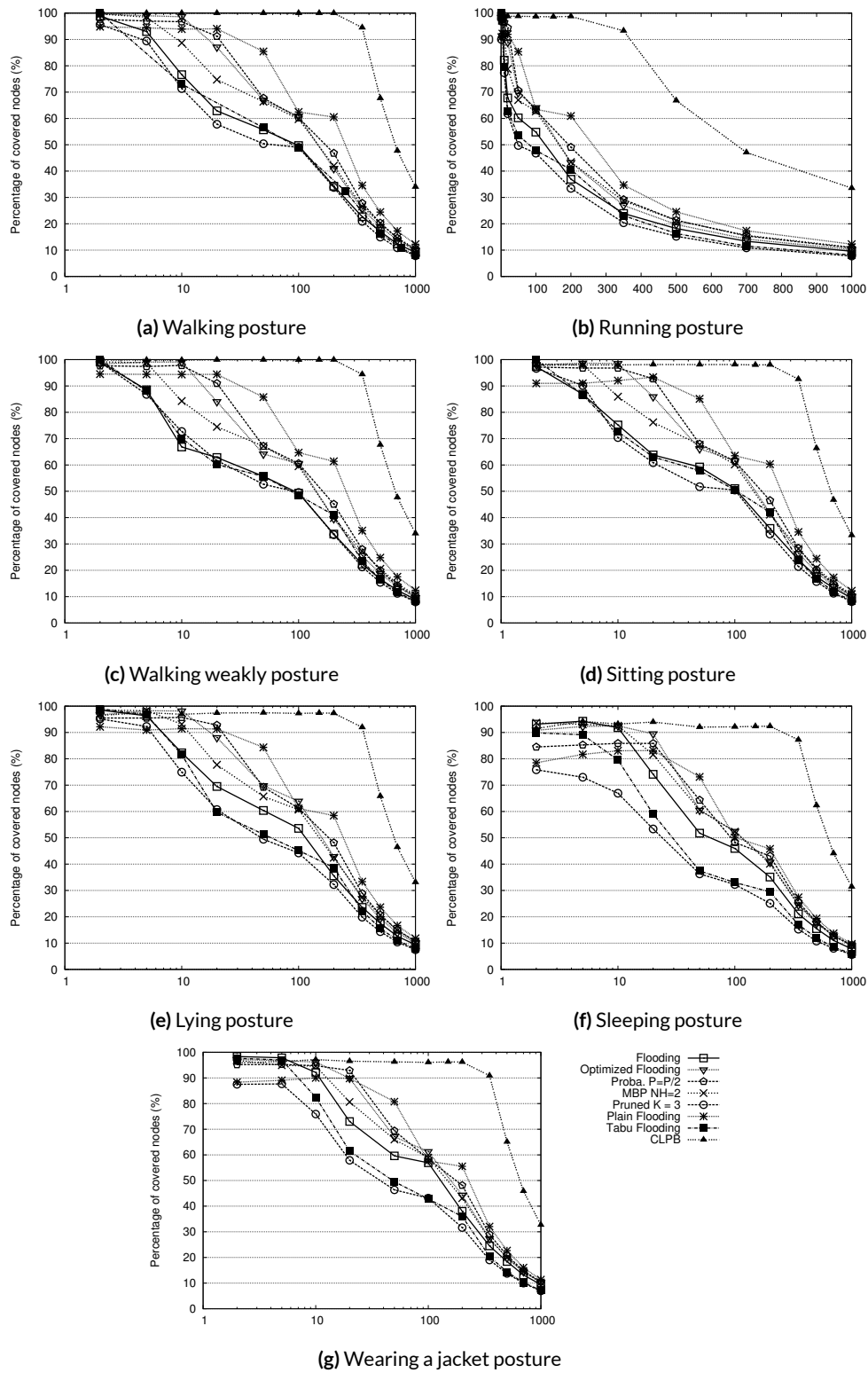


Figure 5.5: Percentage of covered nodes per posture for flat broadcast strategies and CLPB – MAC buffer size

30% of covered nodes by 1000 packets/s. Nodes are no more able to broadcast all waiting packets, then new received packets are dropped because buffer is saturated at MAC level.

MAC buffer size impacts strategies performance. For this reason, we extend our analysis by varying MAC buffer size to pinpoint this impact. Simulation results are presented in section 5.4.2 for a buffer size equals to 200.

PERCENTAGE OF DE-SEQUENCING Figure 5.6 presents the percentage of de-sequencing in function of *Sink* node transmission rate. We evaluate the FIFO order consistency of the different strategies.

Three phases can be observed:

- At the beginning, all strategies present 0% of de-sequencing. At this point, strategies are able to handle more than one packet in the network.
- Then, from a given rate (depending on the strategy), the percentage increases. Here, based on Figure 5.5, the percentage of covered nodes decreases due to collisions. Therefore, sequencing is no longer ensured.
- Finally, the percentage decreases to converge to 0% again due to the fact that few packets are received.

We observe that, for flat broadcast strategies, the inflection points of different curves have the same abscissa. This abscissa corresponds to a transmission rate equal to 100 packets/s. Looking deeper to different set parameters, 100 is the default value of the buffer size at the MAC level.

MBP strategy presents the highest percentage of de-sequencing for all postures, starting from 2 packets/s. In this strategy, nodes can whether broadcast immediately received packet or put it in the buffer and delay broadcast depending on threshold values. Thus, de-sequencing is more feasible.

Percentage of de-sequencing increases starting from 5 packets/s for *Flooding* and *Pruned Flooding* and from 20 packets/s for *Optimized Flooding*, *PlainFlooding* and *Probabilistic Flooding*, for most postures. *Flooding* and *Pruned Flooding* have difficulties to handle transmission rate increase due to collisions and packets loss. An exception with sleeping posture, where the percentage of de-sequencing is observed starting from 10 packets/s due to the characteristics of this posture.

CLPB reacts as the other strategies and we observe de-sequencing in the received sequence. This is due to the mobility model. That is, unreliable links may occur, thus allowing reception of one of several packets from the broadcasted sequence. The links then disappear and the complete sequence will be received through a more reliable link.

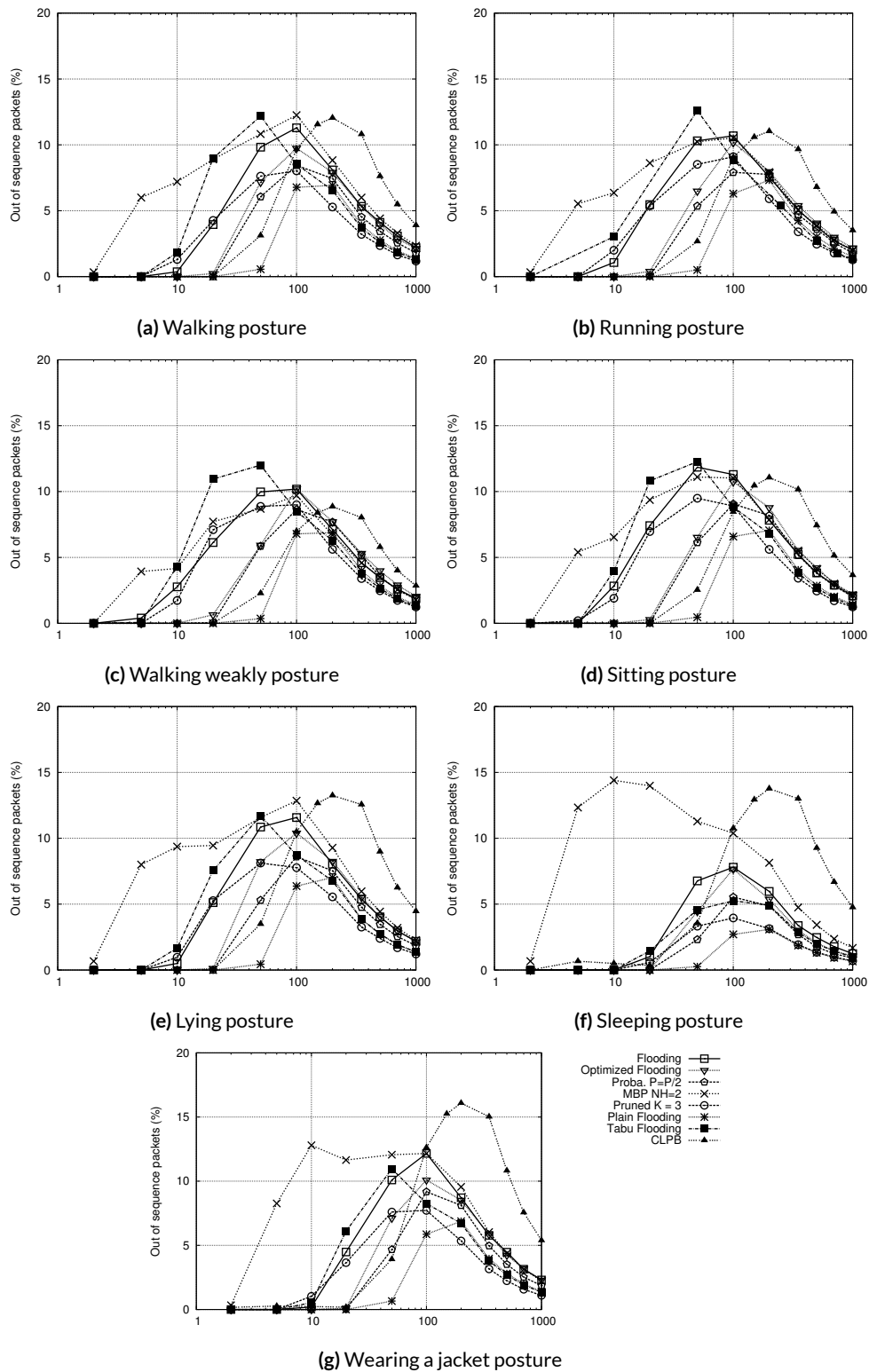


Figure 5.6: Percentage of de-sequencing per posture for flat broadcast strategies and CLPB – MAC buffer size

BROADCAST RATES UP TO 1000 PACKETS/S – MAC BUFFER SIZE 200

MAC buffer size is set to 200 packets. Now, more packets are able to be buffered waiting for broadcast. As for buffer size 100 (paragraph 5.4.2), we present the percentage of covered nodes and the percentage of de-sequencing.

In this section we advocate that, contrary to the expectations, the increase of the buffer size (two times greater than in the previous case) has little impact on the performance of the strategies.

NETWORK COVERAGE Figure 5.7 presents the percentage of covered nodes in function of packets number per second.

Network coverage is no longer assured with increased transmission rate. *Flooding* and *Pruned Flooding* strategies show the lowest percentage due to collisions for both and to the random choice of next hops for *Pruned Flooding*. *Plain Flooding* slightly exceeds the other strategies in walking and running postures. However in sleeping posture (which is a static posture) *Plain Flooding* maximum percentage is 83% against 93% in running and walking weakly postures. In this strategy, nodes broadcast received packets only once, thus number of packets copies in the network is limited. This points out again the impact of collisions. *Optimized Flooding* and *Probabilistic Flooding* performances are close to each others. These two strategies restrict re-broadcasting that allow them to have a slight better result compared to other strategies. However, we can observe, that, to 10 packets/s, *Optimized Flooding* slightly exceeds *Probabilistic Flooding*. This gap is more important in sleeping posture than running and walking postures. Because, *Optimized Flooding* strategy eliminates unnecessary retransmissions towards the end of the broadcasting process while *Probabilistic Flooding* restricts the broadcast from the beginning.

CLPB outperforms the other strategies with a high percentage of covered nodes. It shows high percentage of covered nodes equal to 98% for walking and running postures and equal to 92% for sleeping posture up to 350 packets/s. When the transmission rate is 1000 packets/s, *CLPB* covers 40% of nodes against an average of 10 to 20% for broadcast strategies.

PERCENTAGE OF DE-SEQUENCING Figure 5.8 presents the percentage of de-sequencing in function of packets number per second.

At first glance, results are quite similar to results for a buffer size equal to 100 (paragraph 5.6). Indeed, the percentage of de-sequencing is close for both values. However, in details, results show that the curve is offset and the peak is reached around 200 packets/s whereas it is around 100 packets/s for the previous results. With *CLPB*, the peak reached is reached by 350

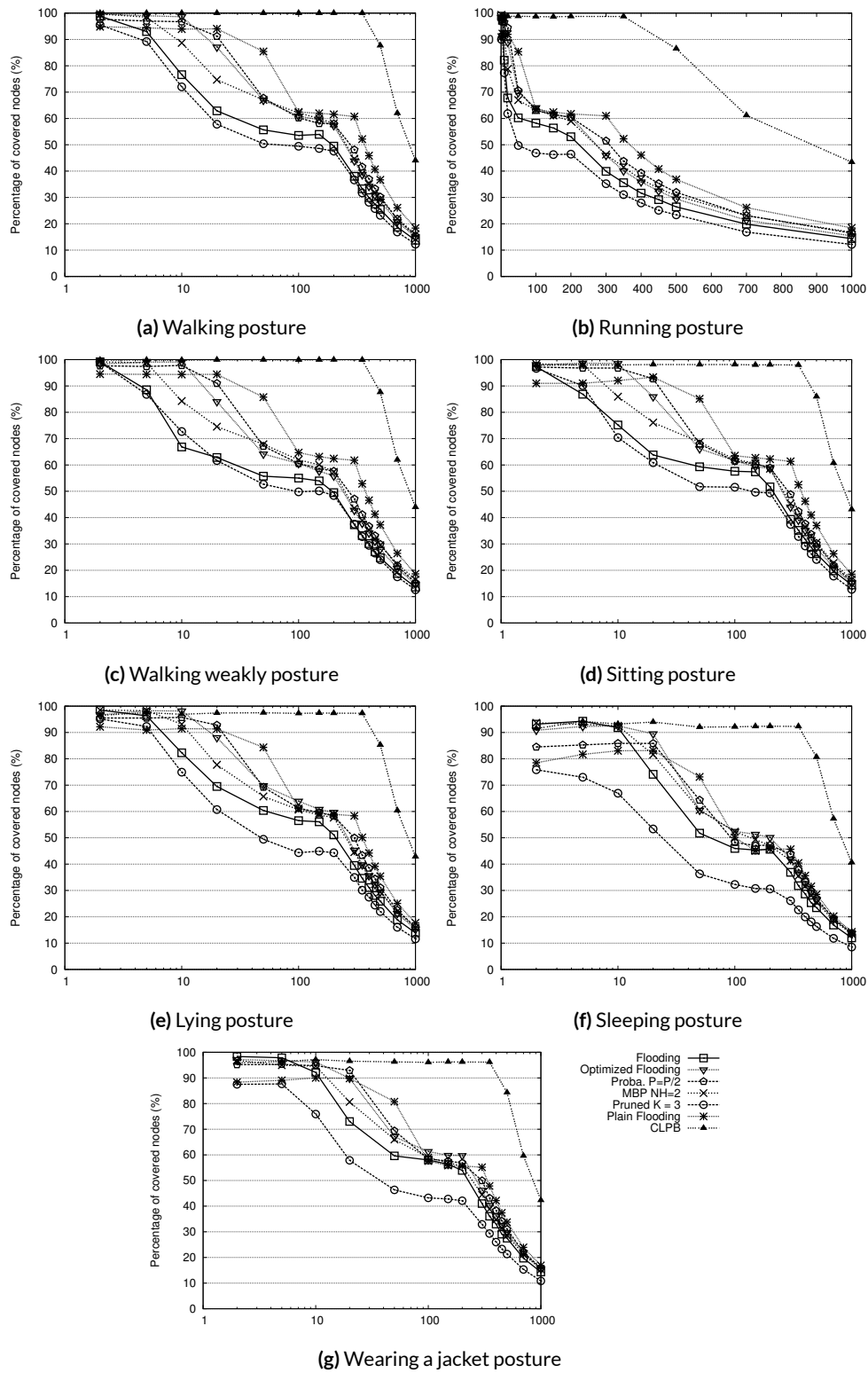


Figure 5.7: Percentage of covered nodes per posture for flat broadcast strategies and CLPB – MAC buffer size

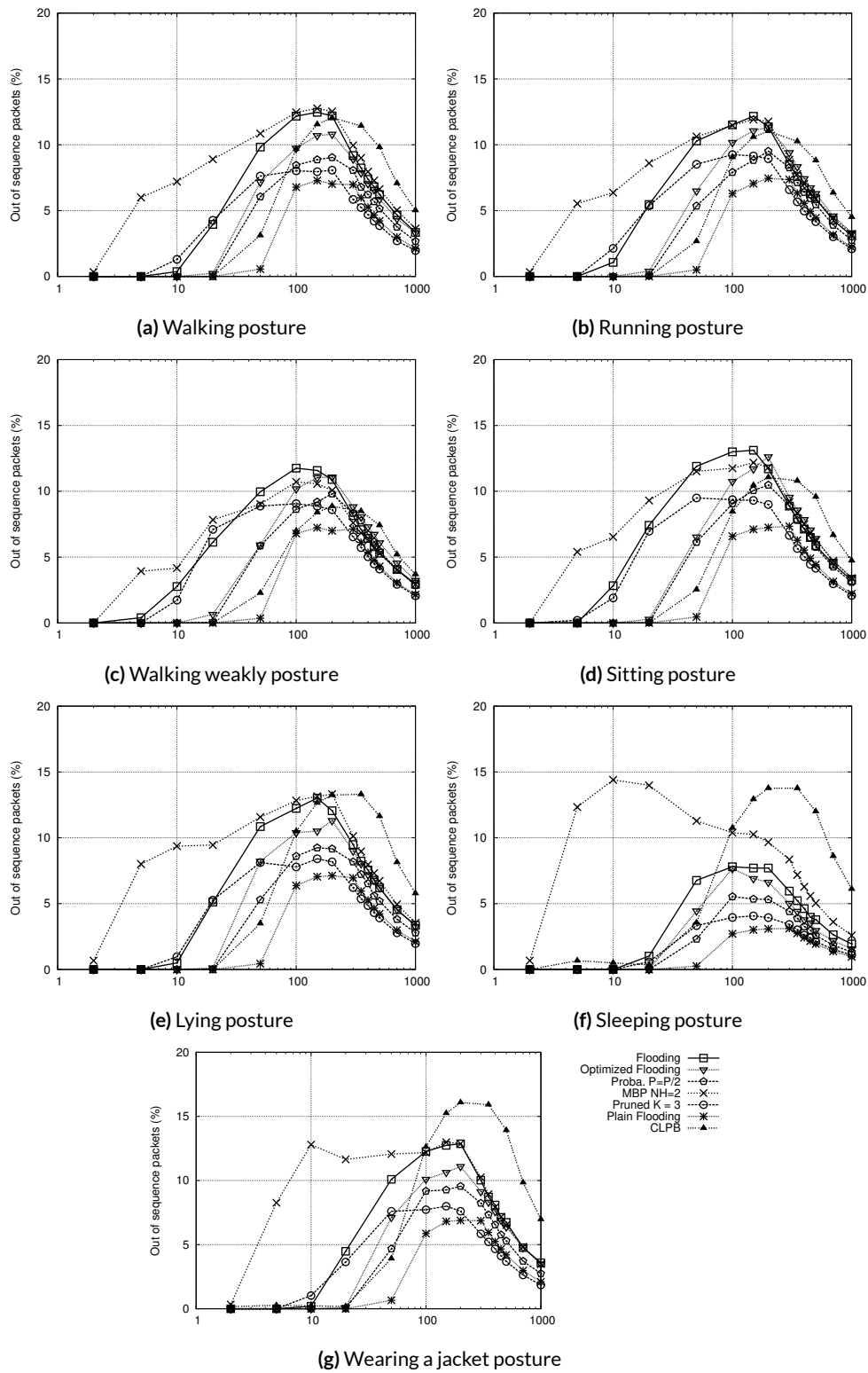


Figure 5.8: Percentage of de-sequencing per posture for flat broadcast strategies and CLPB – MAC buffer size

packets/s, starting from which percentage of both covered nodes and de-sequencing decreases and packets from application layer are not even broadcasted due to MAC over-buffer.

5.4.3 BROADCAST WITH TRANSMISSION RATES OF 1 PACKET/S

The previous study (section 5.4.2) showed that our new cross layer protocol, *CLPB*, outperforms flat broadcast strategies with a *Sink* transmission rate that goes up to 1000 packets/s. The protocol offers a high percentage of covered nodes up to 350 packets/s against 10 packets/s for broadcast strategies.

In the following, we zoom the case when *Sink* transmission rate equals one packet per second. In addition to the percentage of covered nodes and the number of transmissions and receptions we also evaluate the *Latency* per strategy.

NETWORK COVERAGE

Results in figure 5.9 show, in average, a good percentage for all strategies greater than 88%.

Flooding, *Optimized Flooding* and *MBP* show quite close percentages. As expected, with *Flooding* strategy, nodes rebroadcast immediately each received packet which increases the network cover.

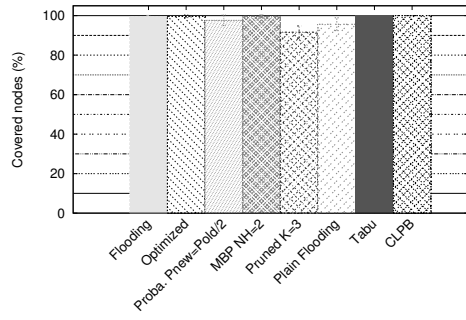
Optimized Flooding is a *Flooding* strategy adaptation with constraints on rebroadcast. Thus, a slight decrease of the percentage (less than 2%) is observed due to discarding obsolete copies of the packet in order to reduce ping-pong effect.

For *MBP*, nodes broadcast each received packet while its number of hops is less than the predefined threshold (in these simulations: $threshold = NH = 2$). In case the threshold is reached i.e packet number of hops is equal to N , then nodes will delay the packet broadcasting waiting for acknowledgements. This explains the good percentage shown by *MBP*.

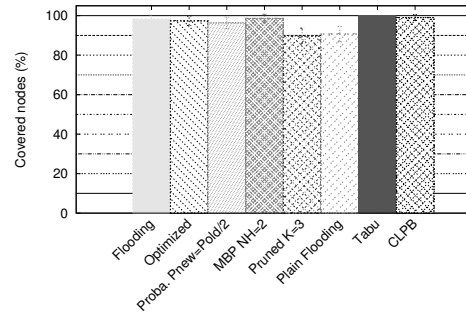
Probabilistic Flooding and *Pruned Flooding* strategies percentage decreases due to randomness in the broadcast process: *Probabilistic Flooding* in the choice of the random variable r to compare with the probability P while *Pruned Flooding* in the choice of the K random nodes as next hops.

Plain Flooding shows the lowest percentage. Nodes broadcast a received packet only once. After that, all received copies are discarded. When a neighbor didn't receive the packet at the unique broadcast attempt, it has less chances to receive it later.

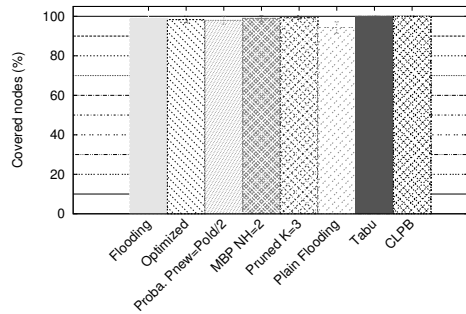
CLPB shows a high percentage, higher than 96%. Although nodes broadcast the packet only once, *CLPB* achieves good network cover and high reliability.



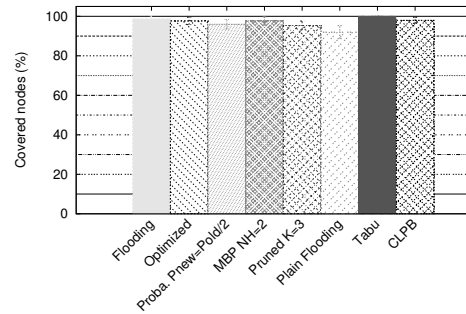
(a) Walking posture



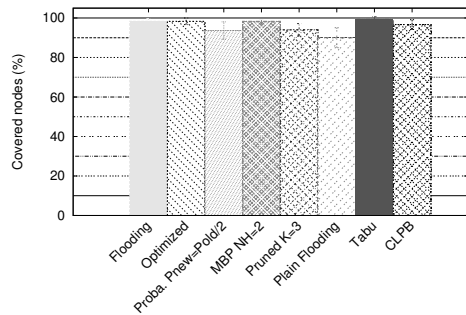
(b) Running posture



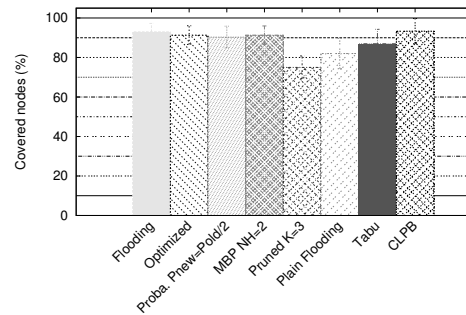
(c) Walking weakly posture



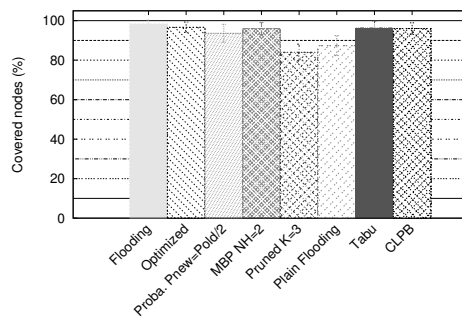
(d) Sitting posture



(e) Lying posture



(f) Sleeping posture



(g) Wearing a jacket posture

Figure 5.9: Percentage of covered nodes for all postures for flat broadcast strategies & CLPB – transmission rate of 1 packet/s

END TO END DELAY

Figure 5.10 shows the average end to end delay per node for all strategies while figure 5.11 shows the average end to end delay per posture.

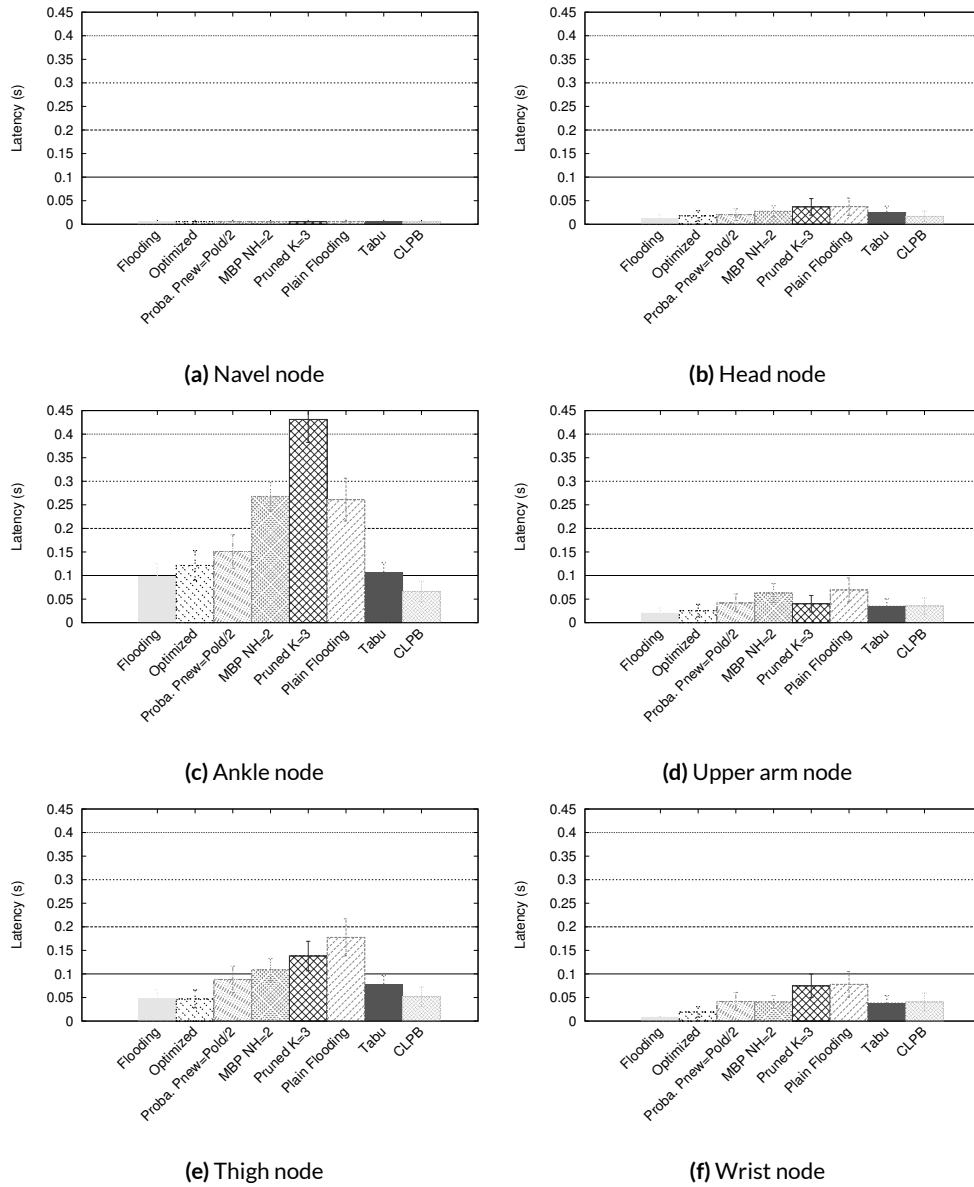


Figure 5.10: Latency per node for flat broadcast strategies & CLPB – transmission rate of 1 packet/s

Flooding and *Optimized Flooding* strategies ensure the best end to end delay between all flat broadcast strategies.

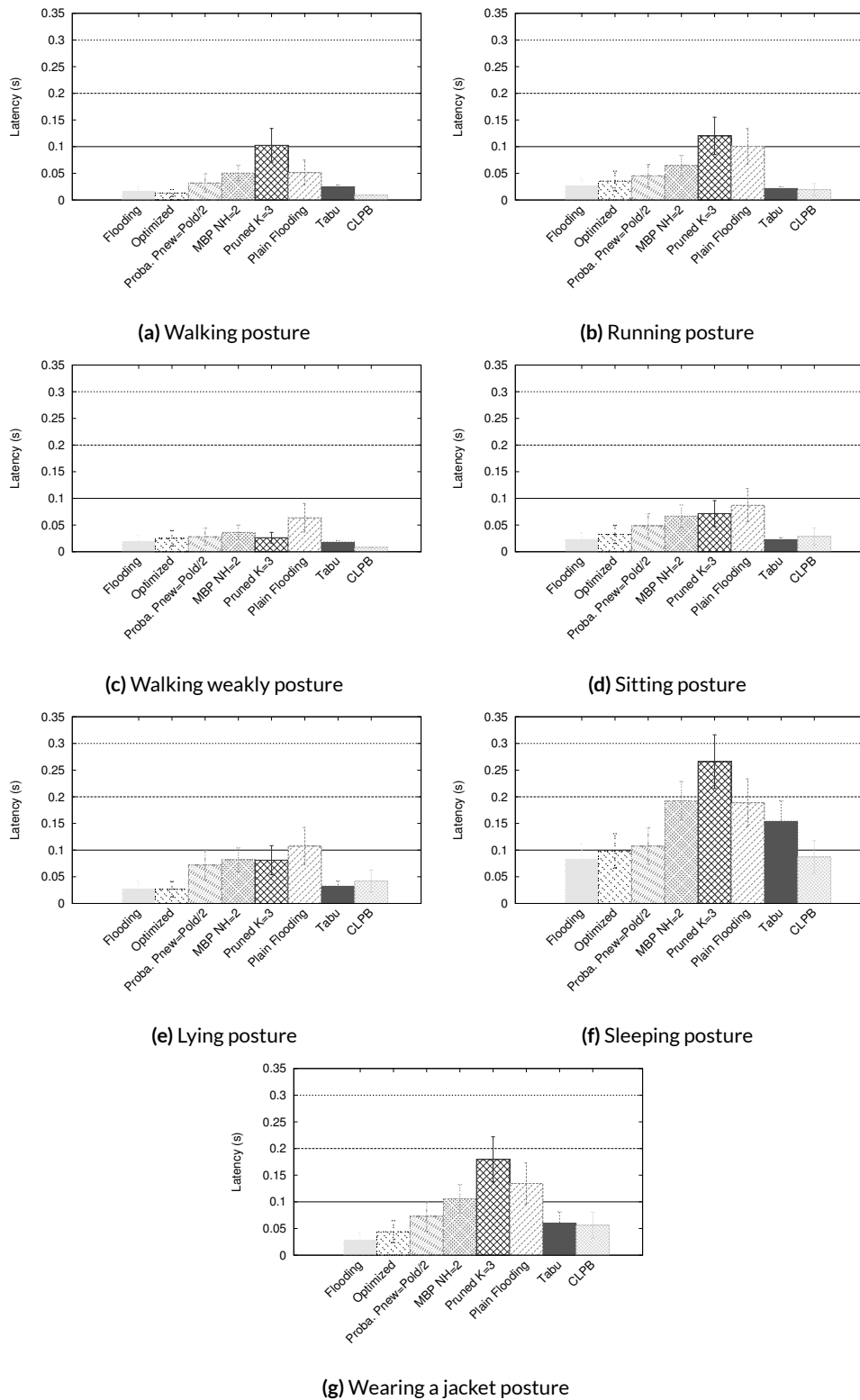


Figure 5.11: Latency per posture for flat broadcast strategies & CLPB – transmission rate of 1 packet/s

In *MBP* nodes delay packet broadcasting in order to allow receivers to acknowledge received packets which entails high latency.

The highest end-to-end delay is observed with *Plain Flooding* and *Pruned Flooding* strategies. It is related to their low percentage of covered nodes. In fact, to each non covered node, a high end to end delay is automatically assigned to this node.

CLPB ensures a low end to end delay close to *Flooding*. Although, sender nodes have to wait for their time slot to broadcast a packet, delay is not affected. This is due to two factors: First, the choice of time slot duration, equal to 0.005s during these simulations. Second, *CLPB* scheduling mechanism avoids collisions, increases transmission success probability, decreases percentage on non-covered nodes and thus reduces end to end delay.

Strategies behave similarly considering nodes position. For nodes at navel and head, a low end to end delay is observed and it is almost equal for all strategies. In fact, these nodes are by a single hop from *Sink* node adding to that, they are almost motionless. A slight increase in delay with upper arm and wrist nodes because, for some postures, these two nodes are moving and signal attenuation becomes important. Thigh and wrist, are the farthest nodes to the *Sink*, thus a packet needs to pass through intermediate nodes before reaching these two nodes which increases end to end delay.

It is important to remark that, to reach ankle node, with our cross layer protocol a broadcasted packet takes half the time it takes with the other strategies even comparing with *Flooding* strategy.

Our novel protocol *CLPB* outperforms *Flooding* in walking, walking weakly and running postures. These postures are variations of walking motions where links are reliable and signals attenuations are moderate. Even if it is considered as a reliable environment for communication, for *Flooding*, it causes more packets exchange, collisions, packets loss and retransmissions.

With sleeping posture, all strategies require more time to cover the network. In this posture, some nodes are hidden by body parts and, due to a motionless posture, they are difficult to reach.

TRAFFIC LOAD

Figure 5.12 shows transmissions and receptions number per node and figure 5.13 shows the average number of transmissions and receptions per posture.

Flooding and *Pruned Flooding* strategies present the highest transmissions and receptions number. For *Pruned Flooding*, with $K = 3$, a node broadcasts three copies of the packet. For *Flooding*, no restrictions on broadcasting which generates many copies of the packet. *Plain Flooding* and *CLPB* have a low transmissions and receptions number. However, back to the end to end delay (Figure 5.11) and the percentage of covered nodes (Figure 5.9), *CLPB* performs

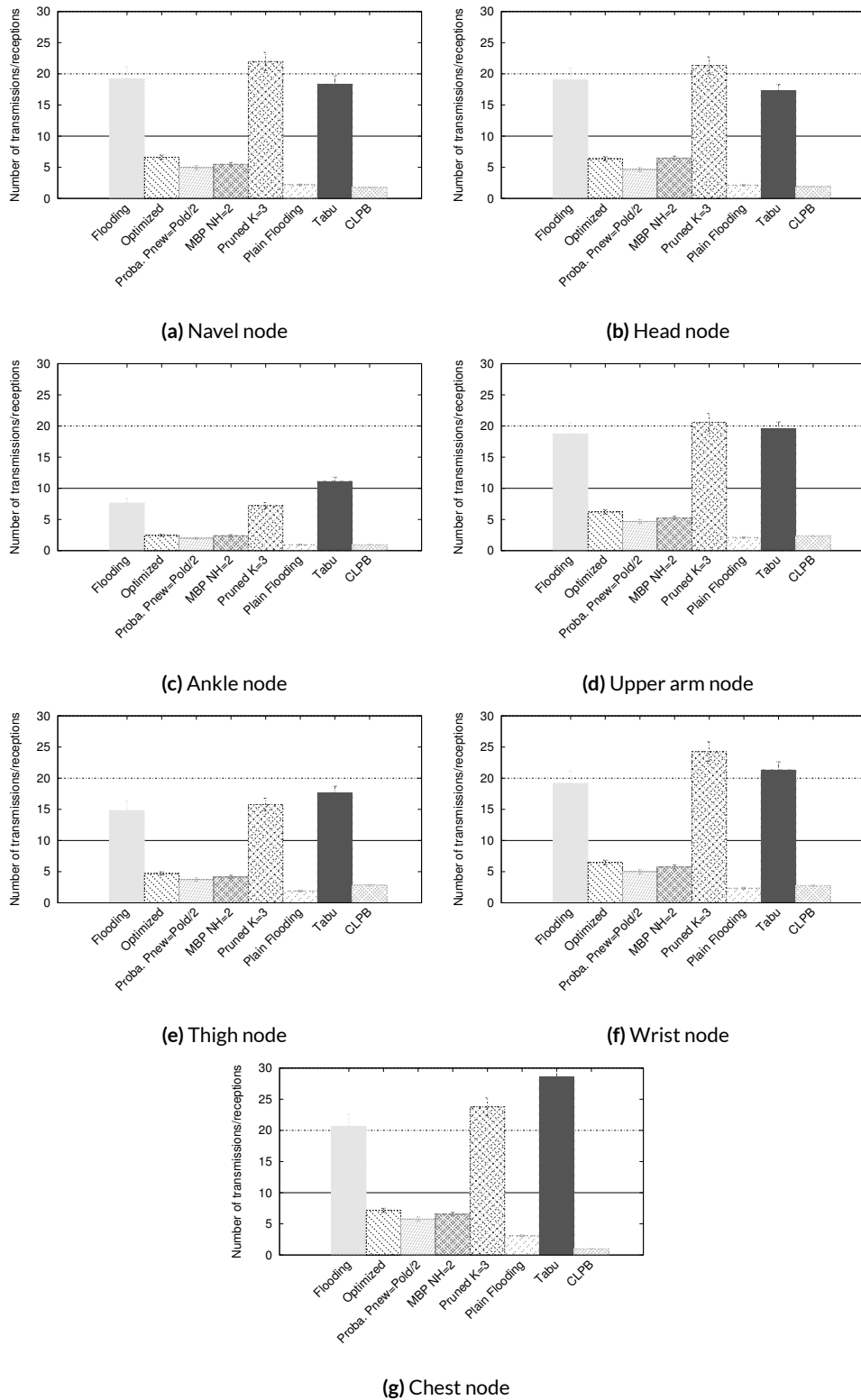


Figure 5.12: Traffic load per node for flat broadcast strategies & CLPB – transmission rate of 1 packet/s

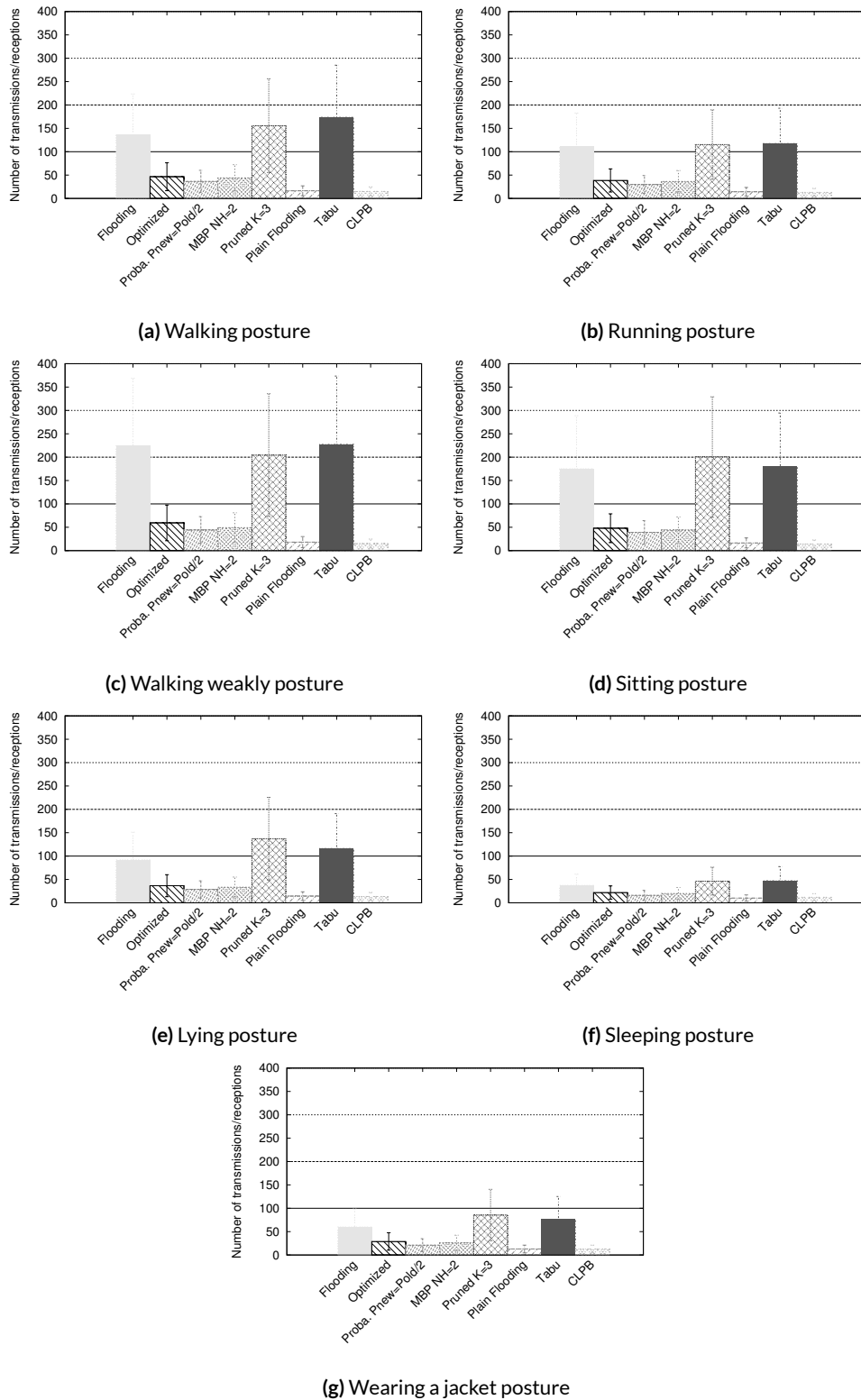


Figure 5.13: Traffic load per posture for flat broadcast strategies & CLPB – transmission rate of 1 packet/s

better. For *Plain Flooding*, this low number is due to lack of communication, while with *CLPB*, this is thanks to scheduling restrictions.

For almost all nodes, *CLPB* presents the lowest transmissions and receptions number. Nodes broadcast only once a received packet during their time slot. Thus, the number of transmissions is, at most, equal to 1 for all nodes. The number of receptions depends on node positions and is at most equal to the number of senders if we suppose that a node is within the range of all the other nodes. For the *Sink* node (chest), there is no receptions. When *Sink* broadcasts the packet in the network, it goes back to sleep and the overall number of transmissions and receptions is equal to 1.

Results show that our new protocol is the less affected by the body posture. Figure shows an almost equal number of transmissions and receptions for all postures. This is explained by a number of transmissions bounded by 1 at most and a number of receptions bounded by *Number of time slots or in other words number of senders*.

For the other strategies, the number of transmissions and receptions varies depending on the wearer posture. We can observe the lowest number with sleeping posture. We observe also that sitting posture presents a high number of transmissions and receptions. This posture is a Up-Down motion variations and is characterized with a dense network where nodes are interconnected. *CLPB offers the best of two worlds: Reliability with a high percentage of covered nodes and low latency with an end-to-end delay close to the best known flat strategy (i.e. Flooding). Simulations results also showed 0 interferences and dropped frames with interference. Collisions between packets are reduced to 0 since at each slot only one node is allowed to transmit. However, there are a number of dropped frames without interferences which is due to our mobility model characteristics.*

SUMMARY

Table 5.1 reports the average values for all simulation, all nodes and all postures per protocol for one single packet transmission.

This table confirms that *CLPB* outperforms flat broadcast strategies even for a low *Sink* transmission rate. Even if network coverage is ensured by all strategies (lowest percentage with *Plain Flooding* 90.28%) including *CLPB*, the latter shows the best end to end delay after *Flooding* strategy and the lowest number of transmissions and receptions (9 times less than *Flooding*).

5.5 CONCLUSION AND FUTURE WORKS

This work is, to the best of our knowledge, the first that proposes a MAC-network cross-layer protocol for broadcast in WBAN. Our work was motivated by results obtained after an extensive set of simulations where we stressed the existing network layer broadcast strategies [28] against realistic human body mobility and various transmission rates.

	Coverage (%)	Latency (ms)	Traffic Load (pkt)
<i>Pruned Flooding</i> $K = 3$	90.85	111.9	134.9
<i>Plain Flooding</i>	90.28	104.7	14.7
<i>MBP</i> $NH = 2$	97.38	85.2	36.0
<i>Probabilistic Flooding</i> ($P_{new} = P_{old}/2$)	95.09	58.1	30.8
<i>Tabu Flooding</i>	97.5	47.6	133.8
<i>Optimized Flooding</i>	97.04	39.3	39.9
<i>Flooding</i>	97.85	31.7	119.2
<i>CLPB</i>	97.57	35.8	13.6

Table 5.1: Average Network coverage, latency and traffic load for all protocols

With no exception, the existing flat broadcast strategies (detailed in chapter 4) register a dramatic drop of performances in terms of percentage of covered nodes, end-to-end delay and energy consumption when the transmission rates are superior to 11Kb/s.

We therefore, propose a new MAC-network cross-layer broadcast protocol that exploits communication graph defined by the body postures in order to optimize medium access and nodes synchronization. Our protocol maintains its good performances up to 190Kb/s transmission rates.

Our work opens several research directions. In the following we discuss two of them. First, we plan to investigate the slot synchronization in WBAN. The cross-layer protocols designed so far for WBAN assume a strong slot synchronization. Efficiently synchronizing slots in WBAN with realistic human body postures and mobility is an open issue. Second, we intend to extend our study to cross-layer converge-cast protocols. Although, there are several proposals in the WBAN literature [46, 36], none of them has been stressed with realistic human body mobility and peaks of transmission rates.

6

Conclusion & Future Directions

6.1 CONCLUSION

In this work we evaluated through simulations the performance of several communication protocols in a WBAN context.

Our simulations were realized with the Omnet++ simulator [212], the Mixim framework [109] and a WBAN channel model proposed in the literature [89]. Simulations were realized over a 7 nodes mobile network in 7 types of movements.

Two communication primitives were studied: *Converge-cast* and *Broadcast*.

In chapter 3, we implemented and evaluated through extensive simulations the performance of 11 WSN and DTN-inspired converge-cast strategies that we classified into three-categories: gossip-based, attenuation-based and multi-path-based strategies. Attenuation-based strategies present good reliability while multi-path based strategies present good delay performance. We further proposed a novel converge-cast strategy *Hybrid* that presents a good compromise in terms of end-to-end delay, resilience to mobility and energy consumption. Our work was published in [31].

In chapter 4, we implemented and compared 9 broadcast strategies. We characterized the compromise between the capacity to flood the whole network quickly and the cost induced by this performance. Our results show that the most complex strategies that require control traffic, or to maintain complex states are not necessarily the most effective. Simple strategies like

Probabilistic Flooding ($P=0.5$ or $P_{new}=P_{old}/2$), which use a probability to forward the packet, or even *Plain Flooding* which never re-forwards a packet already received have a good performance, especially at higher loads. Some strategies, like *Tabu Flooding* which targets only uncovered nodes, or *Pruned Flooding* which forwards packets to a limited number of random neighbors achieve good results when the load is low (one packet) but scale very poorly.

We also proposed and evaluated our own adaptive algorithms. *MBP* [28], for Mixed Broadcast Protocol, applies a more aggressive strategy in the center of the network, where connections are more stable, and becomes more cautious at the border of the network, where a blind transmission has a good chance of success. Although this strategy is very efficient when properly tuned in a low load scenario, its scalability is not satisfactory. Yet, it represents a very good candidate for low traffic networks. *Optimized Flooding* improves the performance of *MBP* by relying on information embedded in the packets and information stored in each forwarder. This strategy shows a promising performance and scales well, which encourages us to realize further studies, including experimentation on a real network.

In chapter 5, to the best of our knowledge, we are the first to propose a MAC-network cross-layer broadcast in WBAN. Our work was motivated by results obtained after an extensive set of simulations where we stressed the existing network layer broadcast strategies [28] against realistic human body mobility and high transmission rates. With no exception, the existing flat broadcast strategies register a dramatic drop of performances in terms of percentage of covered nodes, end-to-end delay and energy consumption when the transmission rates are superior to 11Kb/s. We therefore, propose a new MAC-network cross-layer broadcast that exploits the communication graph defined by the body posture in order to optimize the medium access and nodes synchronization. Our new protocol outperforms existing flat broadcast strategies in terms of percentage of covered nodes, energy consumption and native correct reception of FIFO-ordered messages (i.e. messages are received in the order of their sending). Furthermore, our protocol maintains its good performances up to 190Kb/s transmission rates.

6.2 FUTURE DIRECTIONS

Several future directions are opened by our research.

EXPERIMENTS Currently, we aim to perform experiments to strengthen the quality and the importance of the results.

We already considered experiments with GreenNet ST Microelectronics platform fixed on human skeleton. The platform includes a solar panel to charge the battery and sensors for temperature, pressure, gyroscope and an accelerometer. Our goal was to use this platform as on-body sensor in order to develop and test our new protocols for WBAN. These experiments

and the experimental protocol are established in collaboration with Dr. Koskas - chief of the vascular surgery department in Salpêtrière Hospital Paris, France. Experiments with real human bodies in a hospital environment need special clearances that take several years of administrative negotiations. We therefore cannot provide this kind of evidence for the current manuscript.

In addition, GreenNet platform suffers from many bugs in the code, especially concerning topology and nodes' association and disassociation. Hence, GreenNet platform is no longer in production based on ST Microelectronics' decision.

We are tracking for another platform for experiments' realization and our protocols' evaluation.

SYNCHRONIZATION In chapter 5, we discussed the feasibility of a cross-layer approach in WBAN. We therefore proposed a new MAC-network cross-layer protocol named CLPB. Our work on the cross-layer approach in WBAN opens several research directions. We plan to investigate the slot synchronization in WBAN. The cross-layer protocols designed so far for WBAN assume a strong slot synchronization. Efficiently synchronizing slots in WBAN with realistic human body postures and mobility is an open issue.

In our case, time synchronization is needed for coordinating sensors wakeup. There are different sources of inaccuracies: MAC delay, interrupt latencies upon receiving packet, delay in operating system and in protocol stack. The time stamp point can be at any point in the network layers. The stamping point is critical because it affects the time synchronization accuracy. Indeed, time stamping at an upper layer such as the application layer has the disadvantage that the protocol stack can cause delays that may not be deterministic. We intend to ensure message time stamping at physical layer. In addition, a first thought will be to not generate special synchronization messages, we will use data packets as reference for synchronization, thus no additional power is consumed by transmitting special timing messages.

CROSS-LAYER APPROACH FOR CONVERGE-CAST IN WBAN We intend to extend our work on the converge-cast primitive in WBAN to propose cross-layer converge-cast protocols. Although, there are several proposals in the WBAN literature, none of them has been stressed with realistic human body mobility and peaks of transmission rates. The idea is to improve the best of our strategies by combining them with old and new cross-layer techniques developed for WBAN (e.g. [36, 115]). Another direction is to add to the studied strategies total-order features. Although this problem is crucial for medical applications it has never been investigated in WBAN context.

CHANNEL MODELS IN WBAN A future work would be a detailed study of existing channel models [214] and a comparison with the current model [89].

We can also adapt this work to the context of IR-UWB transmissions, which is a promising technology for WBAN. There exist several frequency bands that can be used in order to transmit information in a wireless BAN. The choice of appropriate bands depends on many parameters (the nature of the application, the required data rate, environment, the number of sensors, etc.). Some bands may be more interesting than others in terms of energy regarding different aspects: hardware consumption, propagation channel attenuation, coding capabilities, potential for routing strategies, etc. Thus, to achieve a comprehensive study that would highlight the potential in terms of energy saving, it is necessary to take into account the human body effects on the communication of all available bands. To do so, propagation channel modeling that describe such scenarios must be developed in such a way that it can be easily integrated in routing algorithms.

INTER-WBANs Another interesting future direction would be to consider collisions among multiple WBANs [91, 108]. We can consider inter-BAN communication, for example, in a doctor's waiting room with ten patients, each one of them is considered as BAN, how can we explore this connectivity between these BANs while making sure not to degrade the performance or neglect the security of the data conveyed by the patient.

DYNAMIC TRANSMISSION POWER The idea is to enable the WBAN network to reconfigure itself, based on the surrounding environment, either to favor communication reliability by increasing the transmission power in presence of ambient noise, or to favor energy efficiency and harmlessness by reducing transmission power and exploit the mobility of the humans.

SECURITY AND PRIVACY With the wireless communication, there are more security constraints than with wired communication. Sensors collect and transmit to the concerned authority users' personal informations including sensitive and critical data. These data require strict security mechanisms to prevent malicious use of them. Data security means data are securely stored and forwarded while privacy means that these informations are visible only to the authorized authorities [124].

Patient-related data is vital and modifying this data would lead to disastrous consequences. Thus, data integrity shall be protected all the time including during storage periods. For example, attackers could report false signals or replay old signals. Data needs to always be kept confidential at a node or a local server. For example, some WBAN applications require information about patient's location that an attacker could use to track a patient. In addition, patient's information should kept available only to the concerned entities.

LARGE-SCALE WBAN One of the principle characteristics of WBAN is the size of the network which is limited to a dozen of nodes that are carefully placed on human body and positions are accurately chosen based on the required sensed information. However, WBAN is facing new communication technologies and already, researchers tend to go beyond the basic case use of BANs towards more ambitious projects such as clothes with thousands of small sensors to have a full monitoring of each millimeter oh the human body or caps/helmets equipped with hundreds of sensors to measure the cerebral activity of the individual.

TIME VARYING GRAPH We aim to investigate WBAN features from a theoretical point of view, where the continuous connections and disconnections between the nodes are seen as the appearance and disappearance of the links in a graph, in order to find a general model that describes WBAN network and free from specific settings of a simulation. The idea is to obtain an analytical results (like bounds) that describe a WBAN from a more general point of view that can help in the conception of a new specific algorithm.

An interesting direction is TVG theory [39] where many concepts have been defined. In particular, most of the basic graph concepts were extended to a new temporal version. In fact as the notion of graph is the natural means for representing a standard network, the notion of time-varying graph is the natural means to represents these highly dynamic infrastructure-less networks. Classic static graphs are described by the couple $G=(V,E)$ where V is the set of nodes and E the set of edges among the nodes. Instead the Dynamic Graphs need of new elements used to describe the modifications on the time, therefore are defined as $G = (V, E, T, \rho, \zeta)$, where T indicates the time instant, ρ is called *presence function* and indicates whether a given edge is available or not at a given time and ζ , called *latency function*, indicates the time spent from a message to cross a given edge if starting at a given date.

List of Publications

PUBLISHED

- 1 W. Badreddine, C. Chaudet, F. Petruzzi, M. Potop-Butucaru : “Broadcast strategies in Wireless Body Area Networks”, 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), Cancun, Mexico, pp. 83-90, (ACM) (2015) [28]
- 2 W. Badreddine, C. Chaudet, F. Petruzzi, M. Potop-Butucaru : “Les Stratégies de Diffusion dans les Réseaux Wireless Body Area Networks”, ALGOTEL 2016 - 18èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, Bayonne, France (2016) [29]
- 3 W. Badreddine, N. Khernane, M. Potop-Butucaru, C. Chaudet : “Convergecast in Wireless Body Area Networks”, Ad Hoc Networks, vol. 66, pp. 40-51, (Elsevier) (2017) [31]

UNDER SUBMISSION

- 1 W. Badreddine, C. Chaudet, F. Petruzzi, M. Potop-Butucaru : “Broadcast Strategies and Performance Evaluation of IEEE 802.15.4 in Wireless Body Area Networks WBAN”, (2016) [30]
- 2 W. Badreddine, M. Potop-Butucaru : “Peak Transmission Rate Resilient Cross-layer Broadcast for Body Area Networks”, n°1702.05031, 15-15 pages, ARXIV (2017) [27]

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