Resource Allocation for HARQ based Mobile Ad hoc Networks

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Introduction

Mobile Ad Hoc Networks (MANETs): infrastructure-free

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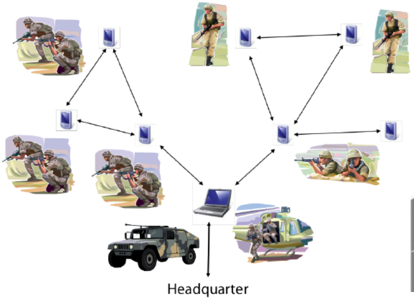
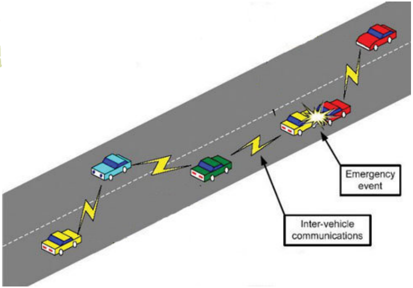
- Highly flexible
- Fast and short-lived communications deployment





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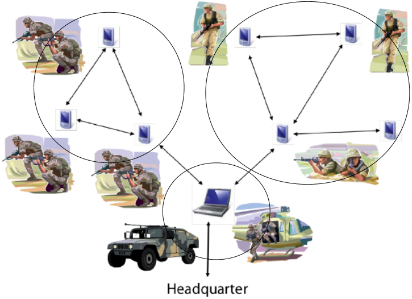
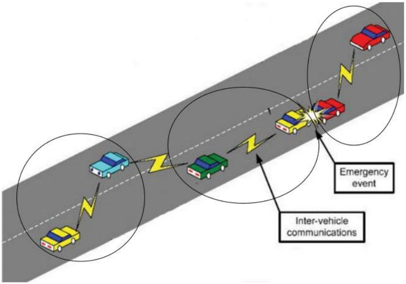
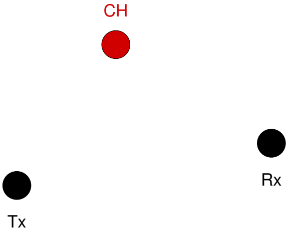




Solution: **Clustered MANET**

Main assumptions



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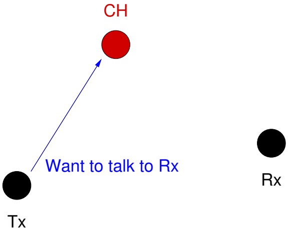

Clustered MANET
$\Rightarrow$ **Centralized** coordination of the **pairwise** communications

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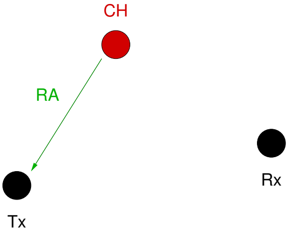

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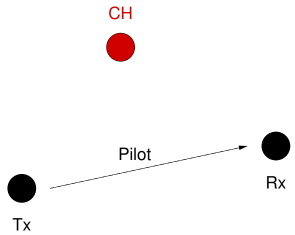

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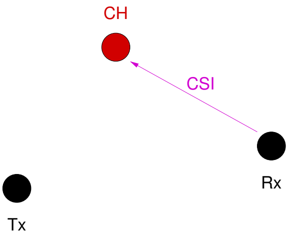

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Feedback latency in MANETs
⇒ Channel **statistics** known at the cluster head

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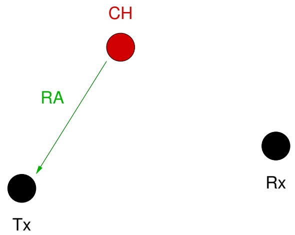

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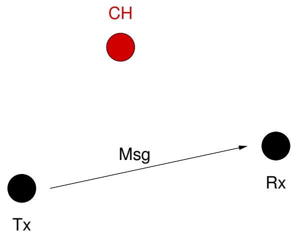

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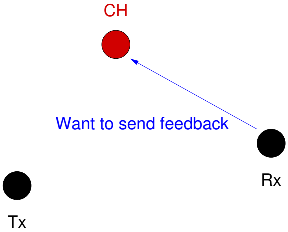

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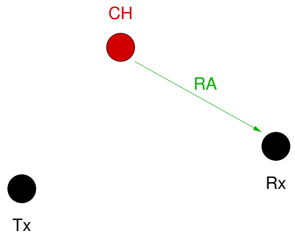

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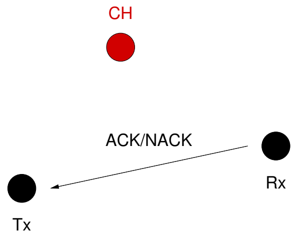

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Thesis contributions

Resource allocation

Allocate the power and bandwidth for Type-I HARQ based users:

- for various PHY layer: finite-length Gaussian codes / practical modulations and codes
- for various Quality of Service (QoS) constraints: rate, rate+PER, rate+delay

Cross-layer Hybrid ARQ optimization (single-user case)

- New closed-form expressions for ARQ metrics
- New MAC packet management: Early-Drop (ED)
- New cross-layer scheme in imperfect feedback context: Report Credit Strategy (RCS)

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Outline

1. Hybrid ARQ at IP level with imperfect feedback
2. Resource allocation in HARQ-based mobile ad hoc networks
3. Resource allocation for HARQ with finite-length Gaussian codes
4. Resource allocation for HARQ with practical MCS

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Hybrid Automatic Repeat reQuest

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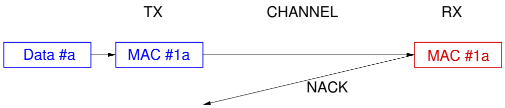
ARQ

Retransmission of the data until correct decoding (or credit used)



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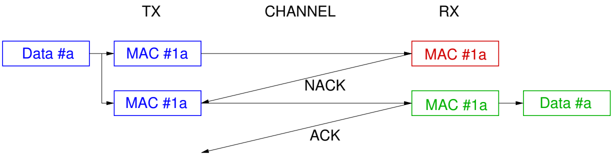

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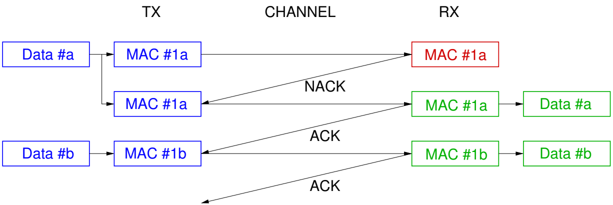
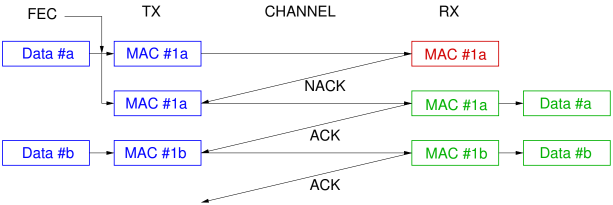


Hybrid Automatic Repeat reQuest

Type-I Hybrid ARQ

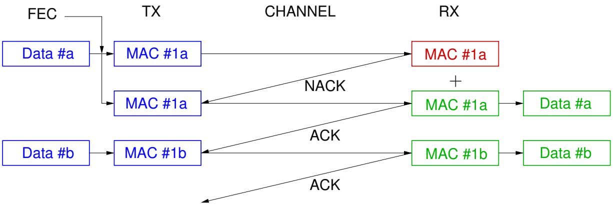
ARQ + Forward Error Correction (FEC)



Hybrid Automatic Repeat reQuest

Type-II Hybrid ARQ

Type-I HARQ + Combination at the receiver side



HARQ performance metrics

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Packet error rate (PER)

Probability of packet transmission failure

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Efficiency

Average number of correctly received bits per transmitted bit

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Packet error rate (PER)

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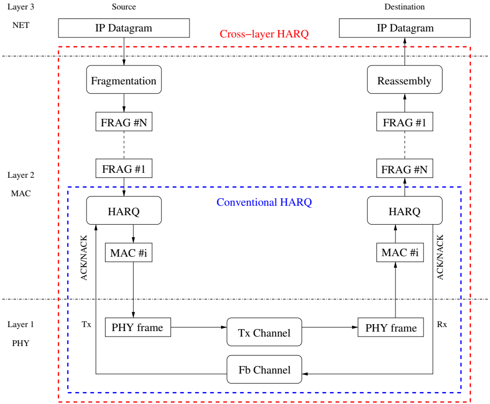
Average number of correctly received bits per transmitted bit

Delay

Average number of MAC packets needed to receive an information packet without error

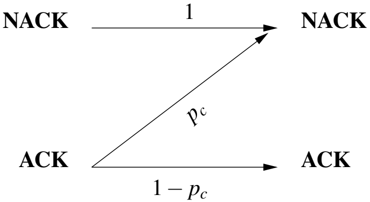
Layer model



Assumptions

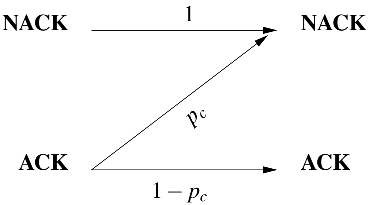
- IP packets are fragmented into N fragments of equal length
- Credit L per fragment (FBS) / Credit C for N fragments (IBS)
- HARQ feedback may be erroneous/delayed in the feedback channel

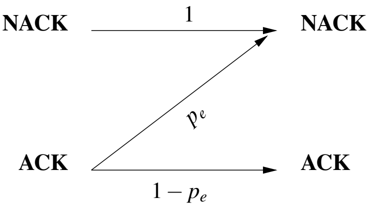
Feedback model



Delayed or erased feedback
(Random arrival and Time-out τ_0)

Feedback model





Delayed or erased feedback
(Random arrival and Time-out τ_0)

Noisy feedback channel
(ACK/NACK errors can be detected)

State of the art and contributions

Feedback \ Layer		MAC	IP
Ideal		[lin'84,wicker'95]	[le duc'12]
Imperfect	Noisy	[wicker'95,malk'00,wu'09]	
	Deterministic Delayed	[lin'84]	
	Random Delayed		
	Noisy + Delayed		

Existing works

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Missing

Contributions

- Closed-form expressions for HARQ performance metrics
- Analysis of imperfect feedback on the performance
- New cross-layer scheme to counteract imperfect feedback

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A new cross-layer HARQ strategy: definition

Idea

- Initial credit per fragment: $L_n^{(0)}$ for fragment #n (as FBS)
- When initial credit $L_n^{(0)}$ not used by fragment #n, then remaining credit added to that of fragment #$(n+1)$ (Report Credit Strategy –RCS–)

Mathematically:

$$L_n \leftarrow L_n^{(0)} + (L_{n-1} - k_{n-1}),\ \forall n > 1$$

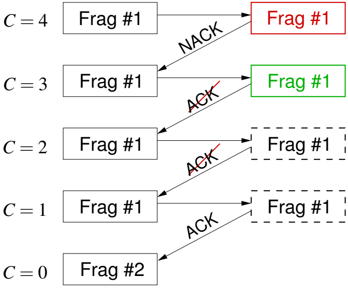
where:

- L_n is the credit for fragment #n after RCS
- $k_n \leq L_n$ is the number of transmissions consumed by fragment #n

A new cross-layer HARQ strategy: example

IBS

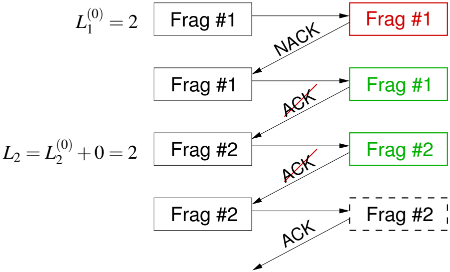
$N = 2$, $C = 4$



IP is KO

RCS

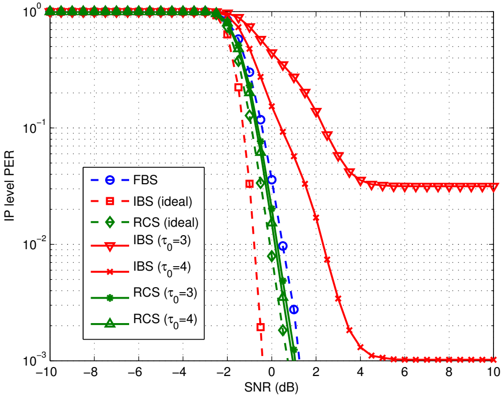
$N = 2$, $\boldsymbol{L}^{(0)} = [2, 2]$



IP is OK

RCS performance (1/2)

Non-instantaneous feedback ($N = 6$, $L = 3$, $C = 18$, $\boldsymbol{L}^{(0)} = [3, 3, 3, 3, 3, 3]$)

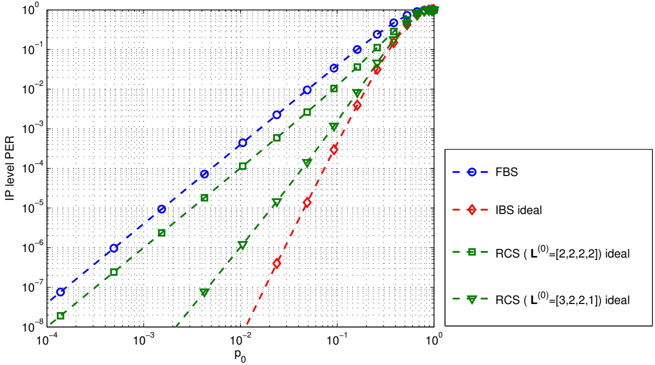


Remark

RCS is more robust to delayed feedback

RCS performance (2/2)

Instantaneous feedback ($N = 4$, $L = 2$, $C = 8$)



Remarks

- Ideal feedback: protecting head fragments gives better performance

RCS performance (2/2)

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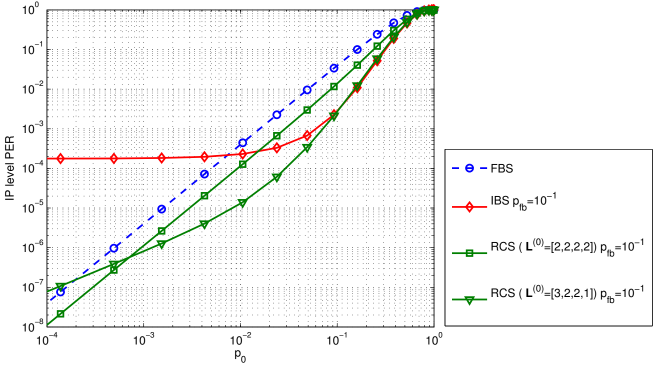

Remarks

- Ideal feedback: protecting head fragments gives better performance
- Nonideal feedback: uniform $\boldsymbol{L}^{(0)}$ is more robust

Summary

Works done for HARQ with imperfect feedback:

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- Definition of RCS, which generalizes the existent cross-layer scheme

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Works done for HARQ with imperfect feedback:

- Definition of RCS, which generalizes the existent cross-layer scheme
- Closed-form expressions of PER, delay, efficiency for RCS with imperfect feedback
- Choice of $\boldsymbol{L}^{(0)}$ in RCS offers a trade-off from cross-layer gain to robustness against imperfect feedback

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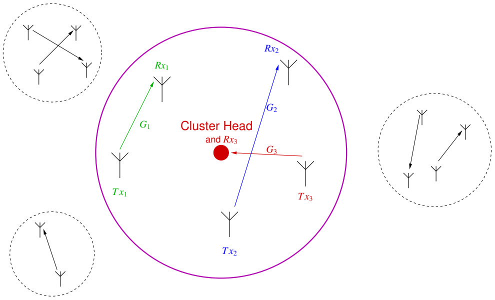
- **Clustered** wireless ad hoc network
- **Statistical CSI** centralized at the Cluster Head
- **HARQ** with finite L to manage fast channel variations



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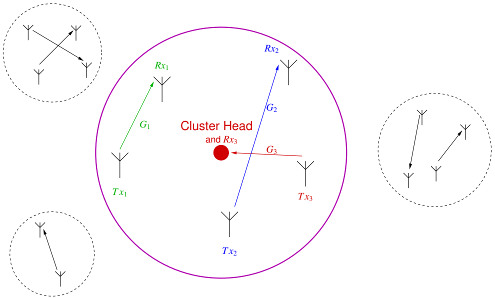

Wireless channel: OFDMA

- PHY layer: cancel ISI due to multipath spread
- Multiple access: cancel multiuser interference inside a cluster

Signal model

- Received signal $Y_k(i,n)$ at subcarrier n of OFDM symbol i for link k:

$$Y_k(i,n) = H_k(i,n)X_k(i,n) + B_k(i,n)$$

with

- $X_k(i,n)$ coded symbol
- $H_k(i,n)$ filter frequency response
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- Statistical channel model: let $h_k(i,m)$ be the m-th filter tap
  - $h_k(i,m)$ independent process (but not i.d.) $\sim \mathcal{CN}(0,\varsigma_{k,m}^2)$
  - $H_k(i,n)$ non-independent in n but i.d. $\sim \mathcal{CN}(0,\varsigma_k^2)$ with $\varsigma_k^2 = \sum_m \varsigma_{k,m}^2$

  $\Rightarrow$ Rayleigh fading channel

  $\Rightarrow$ Channel statistics (for $H_k(i,n)$) independent of subcarrier n

  $\Rightarrow$ Subcarriers are statistically equivalent

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  - $\Rightarrow$ Channel statistics (for $H_k(i,n)$) independent of subcarrier n
  - $\Rightarrow$ Subcarriers are statistically equivalent

Consequence

Bandwidth proportion and energy per subcarrier identical for link k

Resource allocation: design parameters

- Q_k: Energy of link k in OFDM symbol
- γ_k: Bandwidth proportion assigned to link k
- E_k: Energy of link k in entire bandwidth
- Modulation (order 2^m) and coding scheme (rate R)

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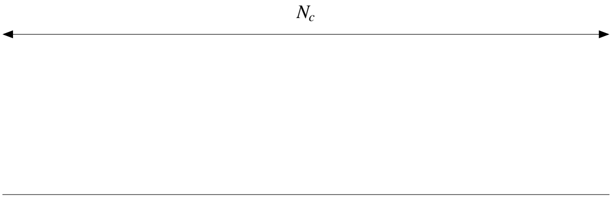

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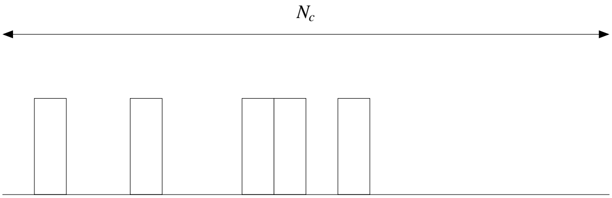

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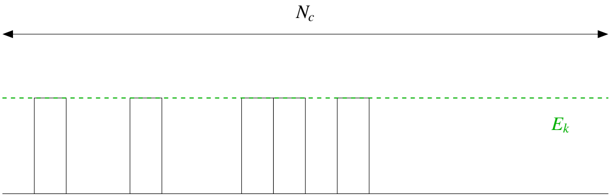

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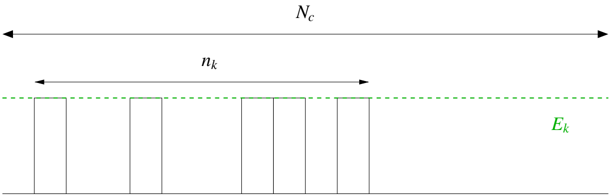

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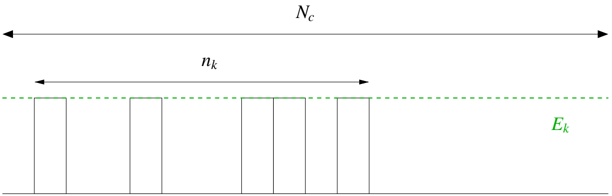

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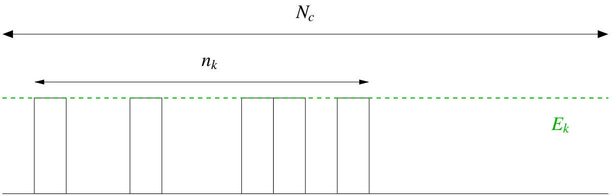

Objective function:

$$\min \sum_{k=1}^{K} Q_k \quad \Leftrightarrow \quad \min \sum_{k=1}^{K} \gamma_k E_k$$

Resource allocation: optimization problem

$$
\min_{(\gamma, \boldsymbol{E})} \sum_{k=1}^{K} \gamma_k E_k \quad \text{s.t.} \qquad \begin{aligned} & \mathbf{QoS}_k(\gamma_k, E_k) \geq \mathbf{QoS}_k^{(0)}, \ \forall k \\ & \sum_{k=1}^{K} \gamma_k \leq 1 \\ & \gamma_k \geq 0, \ E_k \geq 0, \ \forall k \end{aligned}
$$

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$$\sum_{k=1}^{K} \gamma_k \leq 1$$

$$\gamma_k \geq 0,\ E_k \geq 0,\ \forall k$$

QoS and PHY

- Different QoS requirements: rate, rate+PER, rate+delay
- Two PHY implementations: finite-length Gaussian codes, practical MCS

Type-I HARQ QoS metrics

Packet Error Rate:
Probability of packet failure

$$p_0 = g_{m,R}(\mathrm{SNR})$$

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Probability of packet failure

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Goodput:
Average number of received bits / symbol

$$\eta = m R (1 - p_0)$$

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Packet Error Rate:
Probability of packet failure

$$p_0 = g_{m,R}(\mathrm{SNR})$$

Goodput:
Average number of received bits / symbol

$$\eta = m\,R\,(1 - p_0)$$

Delay:
Average number of ARQ transmissions to receive a data packet

$$d = \frac{1}{1 - p_0} - \frac{L\,p_0^L}{1 - p_0^L}$$

Outline

1 Hybrid ARQ at IP level with imperfect feedback

2 Resource allocation in HARQ-based mobile ad hoc networks

3 Resource allocation for HARQ with finite-length Gaussian codes

4 Resource allocation for HARQ with practical MCS

Optimization problem

$$\min_{(\gamma,\boldsymbol{E})} \sum_{k=1}^{K} \gamma_k E_k \quad \text{s.t.} \quad \begin{aligned} & \eta_k(\gamma_k, E_k) \geq \eta_k^{(0)}, \ \forall k \\ & \sum_{k=1}^{K} \gamma_k \leq 1 \\ & \gamma_k \geq 0,\ E_k \geq 0,\ \forall k \end{aligned}$$

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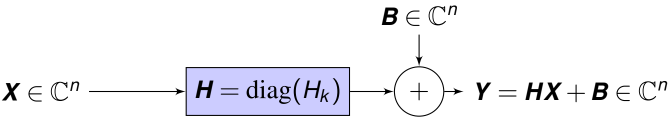
$$\eta_k(\gamma_k, E_k) = \gamma_k r_k (1 - P_e^{(n, r_k)}(\underbrace{G_k E_k}_{\text{SNR}_k}))$$

$P_e^{(n,r)}$ is the error probability of a (n, r) Gaussian code

Error probability of a (n, r) Gaussian code (1/2)



$X_k \sim \mathcal{CN}(0, E_k)$ $\qquad$ $H_k \sim \mathcal{CN}(0, \sigma_h^2)$ $\qquad$ $B_k \sim \mathcal{CN}(0, N_0)$

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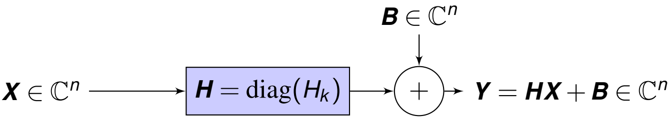

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$P_e^{(n,r)}$ well approximated by the outage probability defined by

$$\Pr\left\{ \underbrace{\frac{1}{n}\sum_{k=1}^{n} i(X_k; Y_k)}_{\text{mutual information rate } (Z_n)} \leq r \right\}$$

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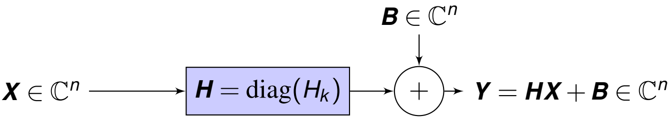

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Problem

Z_n is random for finite n and its cdf has still to be obtained in closed-form

Error probability of a (n, r) Gaussian code (2/2)

For n large enough, Central-Limit Theorem leads to consider that

$$Z_n \sim \mathcal{N}(\mu_n, \sigma_n^2)$$

with

$$\mu_n = e^{1/\overline{\mathrm{SNR}}} E_1(1/\overline{\mathrm{SNR}})$$

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Error probability approximation

$$P_e^{(n,r)}(\overline{\mathrm{SNR}}) \approx Q\left(\frac{\mu_n(\overline{\mathrm{SNR}}) - r}{\sigma_n(\overline{\mathrm{SNR}})}\right)$$

Optimal solution

A solution exists if, and only if,

$$\sum_{k=1}^{K} \frac{\eta_k^{(0)}}{r_k} < 1$$

Optimization problem:

$$\min_{(\gamma,\boldsymbol{E})} \sum_{k=1}^{K} \gamma_k E_k \quad \text{s.t.} \qquad \begin{aligned} & \gamma_k r_k (1 - P_e^{(n,r_k)}(G_k E_k)) \geq \eta_k^{(0)}, \ \forall k \\ & \sum_{k=1}^{K} \gamma_k \leq 1 \\ & \gamma_k \geq 0, \ E_k \geq 0, \ \forall k \end{aligned}$$

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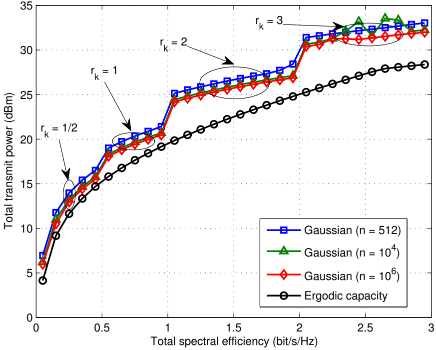
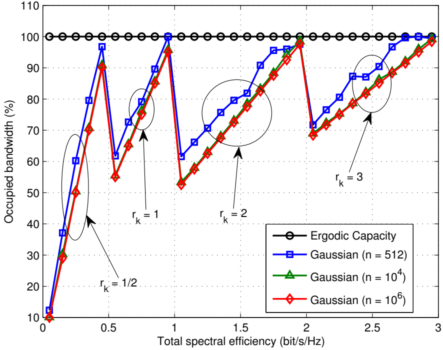
Optimal algorithm

Biconvex optimization problems can be solved optimally [floudas'93]

Allocation results

$K = 2$, $G_1 = 10$ dB, $G_2 = 30$ dB





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- Still a gap for large *n* to ergodic capacity
- Goodput-based allocation saves up to 90% bandwidth

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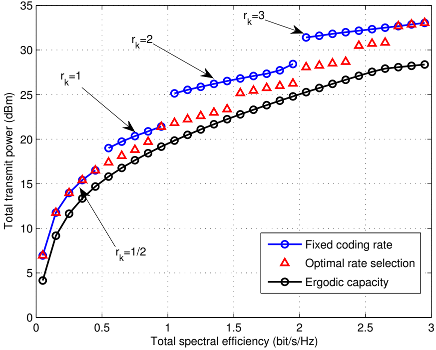
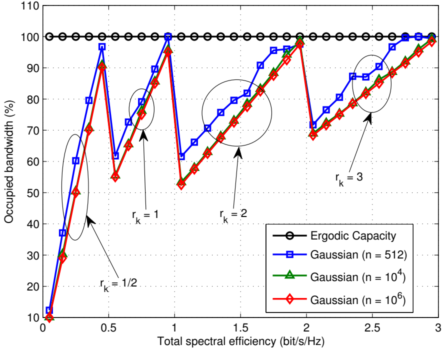
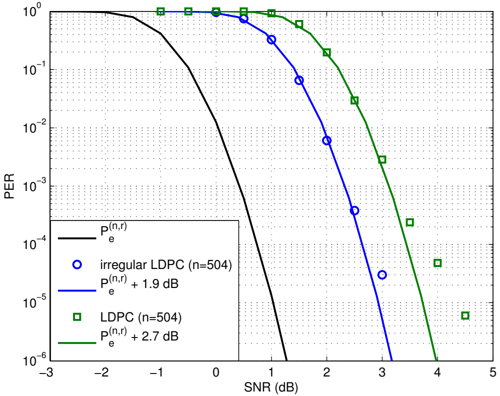




Remarks

- Still a gap for large n to ergodic capacity
- Goodput-based allocation saves up to 90% bandwidth
- Choosing r_k relevantly for being closer to ergodic capacity

How close are powerful FEC codes? ($r = 1/2$)



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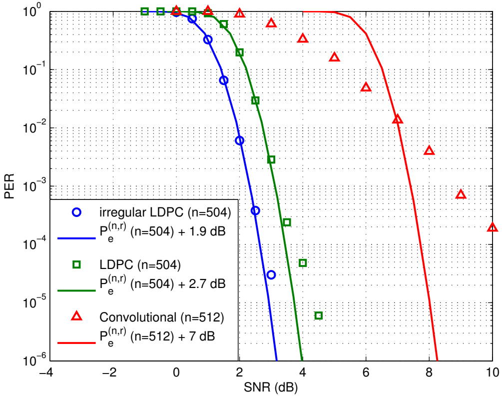

Remark

- Powerful FEC performance well predicted by using an SNR gap
- Not adapted to convolutional codes

Summary

Works done for HARQ-based resource allocation with Gaussian codes:

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Works done for HARQ-based resource allocation with Gaussian codes:

- Closed-form approximation of the error probability of finite-length Gaussian codes on Rayleigh channels
- Optimal algorithm for multiuser power/bandwidth allocation in Type-I HARQ-based MANETs with statistical CSI
- Framework for OFDMA resource allocation in HARQ-based MANETs when LDPC coding is used

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PHY layer abstraction

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Goodput expression

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PER expression

Results are valid for any MCS admitting a parametric PER modelling

Example for simulations

- M-QAM ($m = \log_2(M)$ bits/symb) + Rate-R convolutional code
- Increase diversity to $d_{\min}$
  $\Rightarrow$ Frequency Hopping (FH) + Bit Interleaved Coded Modulation (BICM)
- PER: $P_k(\mathrm{SNR}) \propto \mathrm{SNR}^{-d_{\min}}$

Optimization problem 1: rate constrained

$$\min_{(\gamma,\boldsymbol{E})} \sum_{k=1}^{K} \gamma_k E_k \quad \text{s.t.} \quad \begin{aligned} & \eta_k(\gamma_k, E_k) \geq \eta_k^{(0)}, \ \forall k \\ & \sum_{k=1}^{K} \gamma_k \leq 1 \\ & \gamma_k \geq 0, \, E_k \geq 0, \ \forall k \end{aligned}$$

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Rewritten using $Q_k = \gamma_k E_k$:

$$\boxed{\min_{(\gamma,\boldsymbol{Q})} \sum_{k=1}^{K} Q_k} \quad \text{s.t.} \quad \begin{aligned} &\gamma_k m_k R_k (1 - P_k(G_k Q_k/\gamma_k)) \geq \eta_k^{(0)}, \ \forall k \\ &\sum_{k=1}^{K} \gamma_k \leq 1 \\ &\gamma_k \geq 0,\ Q_k \geq 0,\ \forall k \end{aligned}$$

Problem 1: Results

A solution exists if, and only if, $\sum_{k=1}^{K} \eta_k^{(0)}/(m_k R_k) < 1$

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Power and bandwidth allocation

- We prove that the problem is convex in $(\gamma, \boldsymbol{Q})$ (assuming the PER are convex functions of the SNR)
- Optimal solutions have been exhibited in closed-form (from KKT) given $\text{mcs}_k = (m_k, R_k)$

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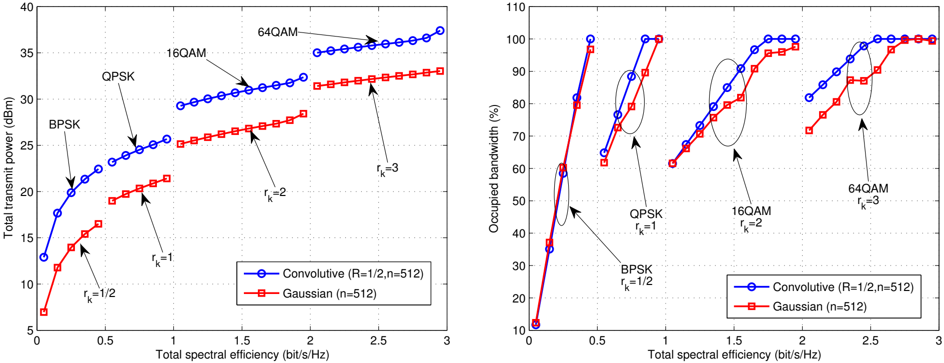
MCS selection

- $(\gamma^*, \boldsymbol{Q}^*) = \arg\min_{(\gamma, \boldsymbol{Q})} \mathcal{Q}_{\mathcal{T}}(\mathbf{mcs})$
- $\mathbf{mcs} \in \mathcal{M}^K \times \mathcal{R}^K \Rightarrow$ Combinatorial Problem
- Greedy heuristic:
  - Modify MCS user by user: $\mathbf{mcs}^{(k)}$
  - Select $k^* = \arg\min_k \mathcal{Q}_{\mathcal{T}}(\mathbf{mcs}^{(k)})$
  - Update MCS if $\mathcal{Q}_{\mathcal{T}}(\mathbf{mcs}^{(k^*)}) < \mathcal{Q}_{\mathcal{T}}^*$

Gap to optimal coding of length $n = 512$

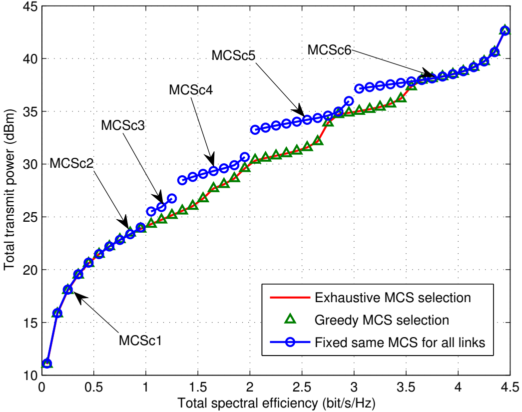
$$K = 2,\ G_1 = 10\ \text{dB},\ G_2 = 30\ \text{dB},\ R_k = 1/2$$



Remarks

- QAM + CC near 4 dB from Gaussian codes
- Same bandwidth saving behavior

MCS selection based on the optimal power/bandwidth policy



Simulation:

- $K = 4$ links
- Free-space path loss
- Random distances in $[50, 1000]$ m

MCS name	MCSc1	MCSc2	MCSc3	MCSc4	MCSc5	MCSc6
m	1	2	2	4	6	6
R	1/2	1/2	2/3	1/2	1/2	3/4
max bit/s/Hz	0.5	1	1.33	2	3	4.5

Optimization problem 2: rate + PER constrained

Problem 1: rate only

$$\min_{(\gamma,\boldsymbol{Q})} \sum_{k=1}^{K} Q_k \quad \text{s.t.} \quad \eta_k(\gamma_k, Q_k) \geq \eta_k^{(0)}, \ \forall k$$

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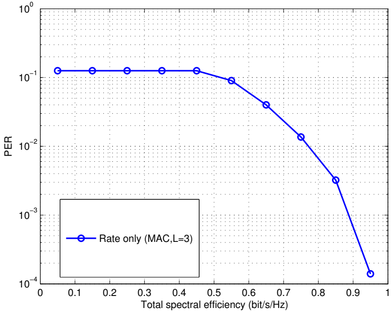

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PER constraint added:

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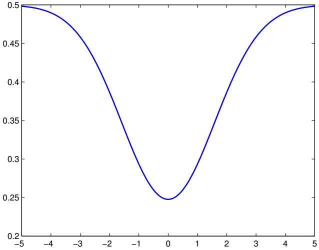
Problem 2: Results

- P_k is a quasi-convex function of (γ_k, Q_k)



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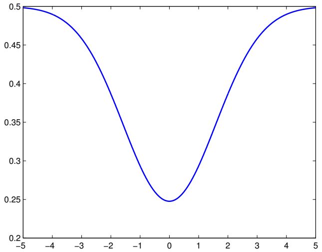

- KKT are optimal [lasserre'10]
  $\Rightarrow$ We extracted the optimal algorithm, but it is $O\left(2^{K-1}\right)\ldots$

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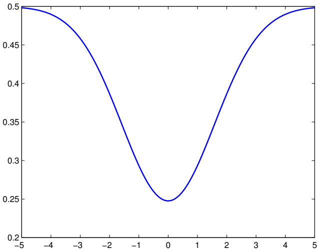

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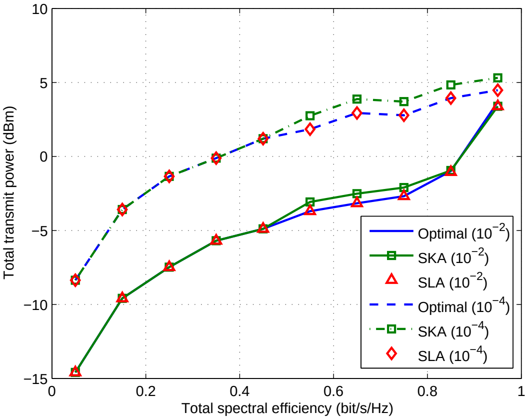
Two suboptimal approaches

- Suboptimal KKT resolution (SKA)
- Suboptimal alternate directional descent $\Rightarrow$ Linear Program (SLA)

Problem 2: Numerical Results (1/2)



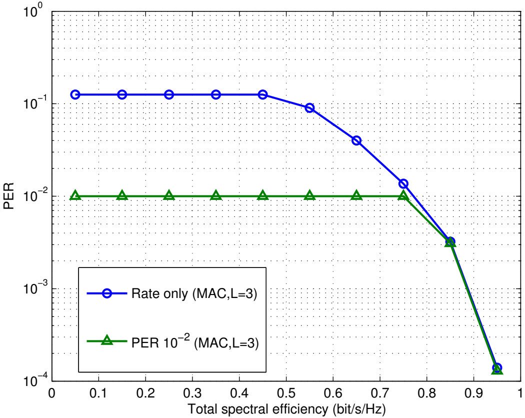
Simulation:

- $K = 4$ links
- Free-space path loss
- Random distances in $[50, 1000]$ m
- Uncoded packets of 128 bits
- BPSK

Remark

SLA offers almost the same performance as KKT

Problem 2: Numerical Results (2/2)



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Remark

- No PER control after allocation defined by Problem 1

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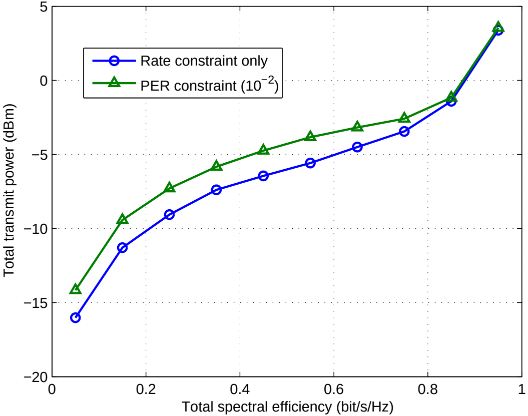

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Remark

- No PER control after allocation defined by Problem 1
- Constraining the PER to 10^{-2} adds an energy cost of about 2 dB

Optimization problem 3: rate + delay constrained

Problem 1: rate only

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Delay function:

$$d_k(\gamma_k, E_k) = \frac{1}{\gamma_k}\left(\frac{1}{1-P_k(G_k E_k)} - \frac{L P_k(G_k E_k)^L}{1-P_k(G_k E_k)^L}\right)$$

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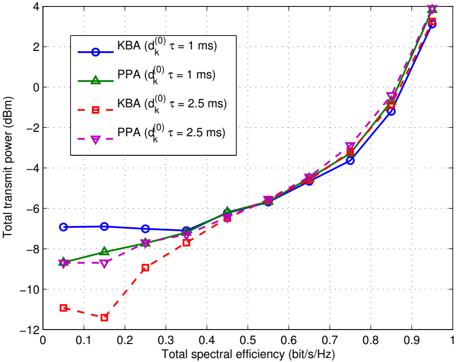
KKT-based algorithm (KBA)

The KKT have been efficiently solved, but no optimality theorem for the designed algorithm

Ping-Pong algorithm (PPA)

Suboptimal algorithm that optimizes alternately in both directions (quasi-convex objective)

Problem 3: Numerical Results



Remarks

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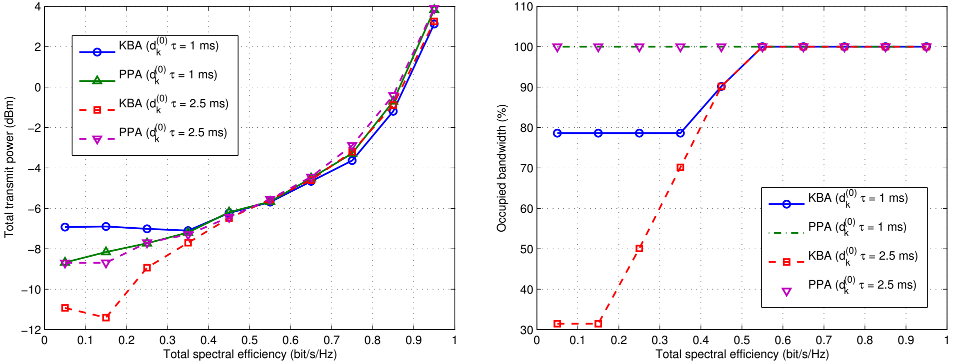

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- PPA fills the bandwidth, KBA saves it

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Thesis perspectives

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Short-term perspectives

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- Distributed allocation to relax the need of CH

Publications

J1. C.J. Le Martret, A. Le Duc, S. Marcille and P. Ciblat: "Analytical performance derivation of Hybrid ARQ schemes at IP layer", *IEEE Trans. Commun.*, vol. 60, no. 5, pp. 1305-1314, May 2012.

J2. S. Marcille, P. Ciblat, and C.J. Le Martret: "Resource Allocation for Type-I HARQ based Wireless Ad Hoc Networks", *IEEE Wireless Commun. Lett.*, vol. 1, no. 6, pp. 597-600, December 2012.

C1. S. Marcille, P. Ciblat, and C.J. Le Martret: "Early-Drop based Hybrid ARQ in a Cross-layer context", *IEEE PIMRC*, September 2011.

C2. S. Marcille, P. Ciblat, and C.J. Le Martret: "Performance computation of cross-layer Hybrid ARQ schemes at IP layer in the presence of corrupted acknowledgments", *IEEE IWCLD*, December 2011.

C3. S. Marcille, P. Ciblat, and C.J. Le Martret: "Stop-and-Wait Hybrid ARQ performance at IP level under imperfect feedback", *IEEE VTC Fall*, September 2012.

C4. S. Marcille, P. Ciblat, and C.J. Le Martret: "Optimal resource allocation in HARQ-based OFDMA wireless networks", *IEEE MILCOM*, October 2012.

C5. S. Marcille, P. Ciblat, and C.J. Le Martret: "A robust cross-layer HARQ scheme for imperfect feedback context", *Asilomar Conference*, November 2012.

C6. S. Marcille, P. Ciblat, and C.J. Le Martret: "On OFDMA resource allocation for delay constrained HARQ systems", *Asilomar Conference*, November 2012.

P1. S. Marcille, C.J. Le Martret, P. Ciblat: "Procédé de retransmission de paquets fragmentés", Patent no. 11/03948.