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Thesis for the degree of Doctor of Philosophy

Data Transmission in the Presence of Limited Channel State Information Feedback

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CHALMERS

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To Mona

Foreword

Modern wireless systems include key technologies such as multi-user diversity, adaptive transmission, multiple-input multiple-output (MIMO) processing and cooperative data communication networks. Common for all these technologies is that the feedback of channel state information (CSI) is necessary, as it is exploited for adapting the transmission parameters, scheduling, etc.

The CSI is normally obtained by direct estimation of the channel coefficients at the receiver and somehow informing the transmitter about the obtained complex fading coefficients. The more information available at the transmitter, the better performance can be achieved. However, depending on the channel characteristics, number of transmit/receive antennas, etc., the rate of the feedback information may be so high that it will consume much of the capacity in the reverse link, making the whole system impractical. Therefore, it has often been questioned whether the improved system performance due to CSI feedback is worth the additional feedback rate and the increased implementation complexity. Thus, different CSI feedback compression techniques have been of interest during the last two decades.

In the thesis, we consider two different approaches, namely, quantized CSI feedback and automatic repeat request (ARQ), providing the imperfect channel quality information at the transmitter. Implementing a quantized CSI feedback scheme, the receiver provides the transmitter with some rough measure of the channel gain before transmission, and the transmitter adjusts its transmission parameters according to this imperfect information. Rough CSI is normally produced by channel gain quantization at the receiver where the set of all possible channel gains is partitioned into a number of non-overlapping regions. The instantaneous channel gain being in a region, its representing symbol is sent back and the transmitter selects the codewords transmission parameters such that the system performance is optimized.

The ARQ, on the other hand, is a well-known approach applied in today's networks to increase the transmission reliability in the absence of the transmitter CSI. From an information-theoretic point of view, the ARQ systems can be viewed as channels with *sequential* feedback where the transmitter CSI is refined in the retransmissions based on the message decoding status. In a general ARQ approach, the transmitter considers some initial transmission rate and power with no pre-knowledge about the channel quality. Then, with the help of ARQ, the decoding status at the receiver will be reported back to the transmitter via one bit feedback. Based on the received feedback, it is decided by the transmitter whether to retransmit the same (or an auxiliary) data or to move on to the

next codeword.

In this perspective, this thesis attempts to study the effect of partial CSI feedback on the performance of different communication networks. To be specific, the thesis investigates the following issues:

- How the partial CSI feedback schemes affect the performance of the wireless networks,
- How we can improve the data transmission efficiency of the communication networks via combination of different CSI feedback approaches,
- The effect of different quality-of-service requirements, e.g., the outage probability or the other users' received interference power, on the performance of the communication setups utilizing partial CSI feedback,
- The effect of power allocation on the performance of the communication systems in different fading conditions.

The results are obtained under block-fading forward channel condition. Moreover, different metrics such as the long-term throughput, the outage probability, the feedback load, the expected delay and the average rate are considered as the performance yardstick, and the results are obtained for different peak and average data transmission power constraints and/or with the other users' received interference constraints.

Keywords: Channel state information, CSI quantization, Hybrid automatic repeat request (HARQ), Adaptive power allocation, Green communication, Outage probability, Long-term throughput, Feedback compression, Bursty communication, Continuous communication, Correlated fading channels, Block-fading channels

Acknowlegments

Time: Sunday 2013-10-13, 5PM.

Place: My office at the S2 department, the place in which I have spent most of the last five years.

It is a long time that I am sitting here trying to find proper words for expressing my feelings. But, it is too hard to concentrate, as my mind goes back to all nice days that I have had. I try my best, although it is far away from the globally-optimal acknowledgement I have in my heart...

First and foremost, I would like to express my deepest gratitude to Professor Thomas Eriksson for being my supervisor and for giving me the opportunity to become a PhD student. Three years ago, in the acknowledgement of my licentiate thesis, I wrote: "I never thought of Thomas as a supervisor, but as a very intelligent, kind and experienced friend ..." But, you are actually much more than a friend to me such that I cannot find a proper name for it except "Thomas." Talking to you is so interesting that I am always worried if I am talking to you in Persian :) I am grateful of your concerns about my research- and non-research-based problems. I recommend everyone to collaborate with you and enjoy your kind, friendly and pure personality.

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My sincerest gratitude and love goes to my family for all the supports they have given me over the years. I am really lucky to have you all. Mom, you have always been a great source of inspiration and encouragement for me. I am always waiting for your phone calls, laughing at funny stories.

Now, I come to the last and the dearest one; Mona. Thank you for being "Mona" and helping me enjoy the life. You have been always with me in all my good and less-good days. Sitting in the sky, God will see us as too tiny particles always moving closely together :) Thank you for your positive mind and supports. Physically and spiritually, you look like the most beautiful flower to me, and your smile worth a world for me. I am very proud of what we have done during the last seven years. A "Thank you" is far from enough for you! I love you.

Sincerely yours,
Behrooz Makki

List of the developed works

The thesis is based on the following publications. The publications with **bold** text are included in the thesis.

1) **Journal papers**

1 **Makki, Behrooz; Eriksson, Thomas: Feedback Subsampling in Temporally-Correlated Slowly-Fading Channels using Quantized CSI, IEEE Transactions on Communications, 61(6), pp. 2282-2294, June 2013.**

2 **Makki, Behrooz; Eriksson, Thomas: On the Performance of MIMO-ARQ Systems with Channel State Information at the Receiver, IEEE Transactions on Communications, revision, 2013.**

3 Makki, Behrooz; Graell I Amat, Alexandre; Eriksson, Thomas: Green Communication via Power-optimized HARQ Protocols, IEEE Transactions on Vehicular Technology, accepted, in press, 2013.

4 Makki, Behrooz; Graell I Amat, Alexandre; Eriksson, Thomas: On ARQ Protocols in Noisy Feedback Conditions, IEEE Transactions on Vehicular Technology, accepted, in press, 2013.

5 Makki, Behrooz; Eriksson, Thomas; Svensson, Tommy: On an HARQ-based Coordinated Multi-point Network, EURASIP Journal on Wireless Communications and Networking, 2013:209, 2013.

6 **Makki, Behrooz; Eriksson, Thomas; Svensson, Tommy: On a Relay-ARQ Network using Adaptive Power Allocation, IEEE Transactions on Communications, submitted, 2013.**

7 Makki, Behrooz; Eriksson, Thomas: On Fairness, Power Allocation and Optimal Channel Quantization in Multiuser Systems Utilizing Multiple Feedback Bits, EURASIP Journal on Wireless Communications and Networking, accepted, in press, 2013.

8 Makki, Behrooz; Eriksson, Thomas: On the Ergodic Achievable Rates of Spectrum Sharing Networks with Finite Backlogged Primary Users and an Interference Indicator Signal, IEEE Transactions on Wireless Communications, 11(9) pp. 3079-3089, Sept. 2012.

9 **Makki, Behrooz; Eriksson, Thomas: On Hybrid ARQ and Quantized CSI Feedback Schemes in Quasi-Static Fading Channels, IEEE Transactions on Communications, 60(4) pp. 986-997, April 2012.**

10 **Makki, Behrooz; Eriksson, Thomas: On the Average Rate of HARQ-Based Quasi-Static Spectrum Sharing Networks, IEEE Transactions on Wireless Communications, 11 (1) pp. 65-77, Jan. 2012.**

11 Makki, Behrooz; Eriksson, Thomas: Multiuser Diversity in Correlated Rayleigh-fading Channels, EURASIP Journal on Wireless Communications and Networking, DOI:10.1186/1687-1499-2012-38, 2012.

12 Makki, Behrooz; Graell I Amat, Alexandre; Eriksson, Thomas: HARQ in Spectrum Sharing Networks, IEEE Communications Letters, 16(9) pp. 1337-1340, Sept. 2012.

13 **Makki, Behrooz; Graell I Amat, Alexandre; Eriksson, Thomas: On ARQ-Based Fast-Fading Channels, IEEE Communications Letters, 16(12) pp. 1921-1924, Dec. 2012.**

14 Makki, Behrooz; Seifi, Nima; Eriksson, Thomas: Multiuser Diversity with Two-Step CSI Feedback, Journal of IET Communications, 6(9) pp. 1119-1125, 2012.

15 Makki, Behrooz; Eriksson, Thomas: CSI Feedback in Correlated Slow-Fading Channels, IEEE Communications Letters, 15 pp. 1294-1297, Dec. 2011.

16 Makki, Behrooz; Eriksson, Thomas: On the Capacity of Rayleigh-Fading Correlated Spectrum Sharing Networks, EURASIP Journal on Wireless Communications and Networking, Vol. 2011, No 1, 83, DOI: 10.1186/1687-1499-2011-83, 2011.

17 Makki, Behrooz; Beygi, Lotfollah; Eriksson, Thomas: Channel Capacity Bounds in the Presence of Quantized Channel State Information. EURASIP Journal on Wireless Communications and Networking, Article Number: 495014, 2010.

18 **Makki, Behrooz; Eriksson, Thomas: On the Average Rate of Quasi-Static Fading Channels with ARQ and CSI Feedback, IEEE communications letters, 14 (9) pp. 806-808, Sept. 2010.**

2) **Conference papers**

1 Makki, Behrooz; Eriksson, Thomas; Svensson, Tommy: Spectrum Sharing via HARQ Feedback and Adaptive Power Allocation, WCNC, submitted, 2014.

2 Makki, Behrooz; Li, Jingya; Svensson, Tommy; Eriksson, Thomas: Coordinated Multi-Point Joint Transmission using Quantized Channel State Information Feedback, European Wireless, pp. 1-5, 2013.

3 Makki, Behrooz; Eriksson, Thomas: Secure Spectrum Sharing via Rate Adaptation, ICNC, pp. 1-5, 2013.

4 Li, Jingya; Makki, Behrooz; Svensson, Tommy; Eriksson, Thomas: Power Allocation for Multi-Point Joint Transmission with Different Node Activeness, WCNC, pp. 4220-4225, 2013.

5 Makki, Behrooz; Eriksson, Thomas: Interference Free Spectrum Sharing using a Sequential Decoder at the Primary Receiver, SPAWC, pp. 154-158, 2012.

6 Makki, Behrooz; Graell I Amat, Alexandre; Eriksson, Thomas: On Optimal Power allocation in Repetition Times Diversity Hybrid Automatic Repeat Request Feedback, WCNC, pp. 2329-2334, 2012.

7 Makki, Behrooz; Li, Jingya; Eriksson, Thomas; Svensson, Tommy: Throughput Analysis for Coordinated Multi-point Networks with Quantized CSI feedback, VTC, pp. 1-5, 2012.

8 Makki, Behrooz; Eriksson, Thomas: Capacity Bounds of Spectrum Sharing Networks with no Channel State Information, European Wireless, pp. 1-5, 2011.

9 Makki, Behrooz; Eriksson, Thomas: Interference Management using One Bit Feedback, European Wireless, pp. 1-5, 2011.

10 Beygi, Lotfollah; Agrell, Erik; Karlsson, Magnus; Makki, Behrooz: A Novel Rate Allocation Method for Multilevel Coded Modulation, ISIT, pp. 1983-1987, 2010.

11 Makki, Behrooz; Eriksson, Thomas: Efficient Channel Quality Feedback Signaling using Transform Coding and Bit Allocation, VTC, pp. 1-5, 2010.

12 Makki, Behrooz; Eriksson, Thomas: Data Transmission in the Presence of Noisy Channel State Feedback and Outage Probability Constraint, ISITA, pp. 458 - 463. ISBN/ISSN: 978-142446017-5, 2010.

13 Makki, Behrooz; Eriksson, Thomas: Data Transmission in the Presence of Channel State Feedback and Outage Probability Constraint, VTC, pp. 1-5, 2010.

3) **Thesis and reports**

1 Makki, Behrooz: Data transmission in the presence of channel state information feedback. Licentiate thesis, Goteborg : Chalmers University of Technology, 2011.

2 D'Amico, Valeria; Halbauer, Hardy; Aronsson, Daniel; Botella, Carmen; Brueck, Stefan; Ciochina, Cristina; Eriksson, Thomas; Fritzsche, Richard; Gesbert, David; Giese, Jochen; Gresset, Nicolas; Lakshmana, Tilak Rajesh; Makki, Behrooz; Melis, Bruno; Abildgaard Olesen, Rikke; Pablo, Maria Luz; Phan Huy, Dinh Thuy; Saur, Stephan; Sternad, Mikael; Svensson, Tommy; Zakhour, Randa; Zirwas, Wolfgang: EU FP7 INFSO-ICT-247223 ARTIST4G, D1.2 Innovative advanced signal processing algorithms for interference avoidance.

Contents

Abbreviations

ACK	ACKnowledgement
ARQ	Automatic Repeat Request
bpcu	Bits per Channel Use
bps	Bit per Slot
BS	Base Station
CDF	Cumulative Distribution Function
CoMP	Coordinated Multi-Point
CSI	Channel State Information
CSIR	Channel State Information at the Receiver
CSIT	Channel State Information at the Transmitter
cu	Channel Use
DCT	Discrete Cosine Transform
DMDT	Diversity-Multiplexing-Delay-Tradeoff
DMT	Diversity-Multiplexing-Tradeoff
EDGE	Enhanced Data GSM Environment
GSM	Global System for Mobile
HARQ	Hybrid Automatic Repeat Request
INR	INceremental Redundancy
KKT	Karush-Kuhn-Tucker
LTE-A	Long-Term Evolution Advanced
MIMO	Multiple-Input and Multiple-Output
MISO	Multiple-Input and Single-Output
MLT	Multi-Layer Transmission
MMSE	Minimum Mean Square Error
NACK	Non-ACKnowledgement
OFDM	Orthogonal Frequency-Division Multiplexing
PDF	Probability Density Function
PU	Primary User
QoS	Quality-of-Service

RTD	Repetition Time Diversity
SINR	Signal-to-Interference-and-Noise Ratio
SISO	Single-Input and Single-Output
SLT	Single-Layer Transmission
SNR	Signal-to-Noise Ratio
SU	Secondary User
TDMA	Time Division Multiple Access
UWB	Ultra WideBand
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

Part I

Introduction

Chapter 1

Introduction

1.1 Communication systems overview

A simplified model of a communication system can be illustrated as in Fig. 1.1. The goal is to send a message from a transmitter to a receiver over a communication *channel*. The channel is normally represented by $\Pr(y|x)$, i.e., a conditional probability density of the output y given the input x. The channel represents the randomness added to the transmitted signals, which may come from interference, thermal noise, the physical medium, etc.

At the transmitter, an integer message m, taking values on the set $\{1, \ldots, 2^{RL}\}$, is mapped into a sequence of symbols of length L and is sent to the receiver (encoding). This sequence is denoted a codeword of length L channel uses (cu) and the set of all possible 2^{RL} codewords is called a codebook. The codebook is known by both the transmitter and the receiver. At the receiver, the sequence y is received and the decoder attempts to detect the transmitted message based on the received sequence (decoding). The result is the decoded message $\hat{m} \in \{1, \ldots, 2^{RL}\}$, as shown in Fig. 1.1. In this way, the communication system attempts to use L channel uses to convey RL bits of information. Thus, the rate of the data is said to be R bits per channel use (bpcu).

In general, the objective is to increase the data rate as much as possible and, at the same time, keep the error probability $\Pr(m \neq \hat{m}, \forall m)$ as low as possible. The optimization is normally carried out under some physical cost function associated with the codewords such as average or peak transmission power constraints.

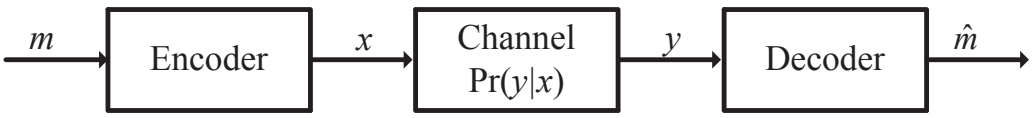


Figure 1.1: A simple illustration of a communication system.

1.2 Block-fading channels

According to the broad literature of wireless communications and the recent standard models, there are many examples of practical communications taking place across block-fading channels. This channel model implies that the fading coefficient between the transmitter and the receiver remains constant over the duration of several symbol transmissions and then it changes according to the fading probability density function (pdf). This time duration is normally called *channel coherence time* , L_{c}, and every occurrence of the fading channel is denoted a *fading block*.

In this way, considering a single-user single-antenna setup, the signal received at the m-th time slot is obtained by

$$Y_m[i] = \sqrt{T_m} h_m X_m[i] + Z_m[i], i = 1, \ldots, L. \tag{1.1}$$

Here, $L \leq L_{\mathrm{c}}$ is the length of the codeword, $X_m[i], i = 1, \ldots, L$, $\frac{1}{L}\sum_{i=1}^{L} |X_m[i]|^2 = 1$, is the power-limited transmission codeword and h_m is the fading coefficient. Also, $Z_m[i] \sim \mathcal{CN}(0,1)$ denotes an independent and identically distributed (i.i.d.) complex Gaussian noise added at the receiver and T_m is the transmission power that, because the noise variance is set to 1, represents the transmission signal-to-noise ratio (SNR) as well (in dB, the SNR is given by $10\log_{10}(T_m)$). Finally, we define $g_m = |h_m|^2$ as the *channel gain* random variable which follows the pdf $f_G(g)$.

The block-fading model is an appropriate model for slowly varying channels, which is common in many practical wireless communication setups. For instance, the block-fading channel is a suitable model for orthogonal frequency-division multiplexing (OFDM) transmission over slowly-varying channels. This is interesting when we remember that OFDM is currently employed as one of the core technologies in many wireless communication standards, such as IEEE 802.11 wireless local area network (WLAN) [1], IEEE 802.16 worldwide interoperability for microwave access (WIMAX) [2] and the digital audio/video broadcasting (DAB/DVB) systems [3, 4]. Also, it is well agreed that, with some optimistic assumptions, the OFDM can often be applied to convert a frequency-selective channel into a set of parallel block-fading channels [5]. Moreover, as demonstrated in, e.g., [6, 7], frequency hopping techniques, as encountered in the global system for mobile communications (GSM) and the enhanced data GSM environment (EDGE), can be also modeled as a block-fading channel. Finally, for further discussions about the fading channel models, the readers are referred to, e.g., [8, 9, 10, 11], which present remarkable equivalences between the block-fading and continuous-fading models, when the Doppler spectrum of the continuous-fading model is bandlimited.

For delay-insensitive applications, the receiver can wait for an unlimited amount of time before decoding the message. Thus, a codeword can be assumed to span an infinite number of fading blocks, and exploit a significant amount of time diversity. This setup is normally referred to as an ergodic channel in the literature [5]. On the other hand, for delay-sensitive applications such as real-time voice and video transmission, a codeword can only span a finite, typically small, number of fading blocks. The length of each fading block, where the channel gain remains constant, is normally large enough to allow information theoretic bounds to kick in and average out the effect of the noise. Hence, studying

the system behavior in the limit of long block length still makes sense. Throughout the thesis, we study the delay-sensitive applications with codewords spanning a finite number of blocks. More specifically, three different scenarios are studied as demonstrated in Fig. 1.2:

- Long-L_c scenario: In this case, the length of the blocks, L_c, is assumed to be so long that many codewords are transmitted in a single fading block. That is, the channel is supposed to remain fixed during the transmission period of many codewords and then change according to the fading pdf. This is an appropriate model for networks with stationary or slow-moving users [12, 13, 14, 15, 16] and we often refer to this fading model as *quasi-static*.

- Short-L_c scenario: Here, the codewords lengths are considered to be the same as the fading block length L_c such that the channel changes after each codeword transmission. The results of this part are useful for modeling users with medium/fast speeds and for the frequency hopping techniques [17, 18, 19, 20, 21, 22]. We denote the channel model corresponding to the short-L_c scenario by *slow-fading*.

- Very short-L_c scenario: For fast-moving users or users with long codewords compared to the channel coherence time, the channel may change during each codeword transmission. For instance, the indoor ultra wideband (UWB) channels normally vary smoothly during a codeword transmission [23, 24]. On the other hand, modern codes often use very long codewords, which may exceed the channel coherence time [14, 25, 26]. In these cases, a finite number of fading realizations may be experienced during a codeword transmission. The fading model associated with the very short-L_c scenario is denoted *fast-fading* throughout the thesis.

For the analytical analysis, the channel variations between the successive blocks are normally supposed to occur independently, i.e., the fading realizations are assumed to be temporally-independent. In this chapter, the results are obtained for the temporally-independent block-fading channels. Extension of the results to the temporally-correlated block-fading channels can be found in paper B, which is appended to the thesis, as well as in the related reports by us and others, e.g., [27, 28, 29, 30, 31, 32, 33, 34].

1.3 Channel state information

Due to the channel block-fading behavior, channel state estimation at the receiver is relatively simple and incurs negligible loss in the transmission rate [5, 6, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25, 26, 35]. A communication scheme that only relies on the channel state information at the receiver (CSIR) is normally called an *open-loop communication system*, as it only supports the forward link transmission[1].

[1]Since there is no instantaneous information available at the transmitter, we denote this scheme *no knowledge case*.

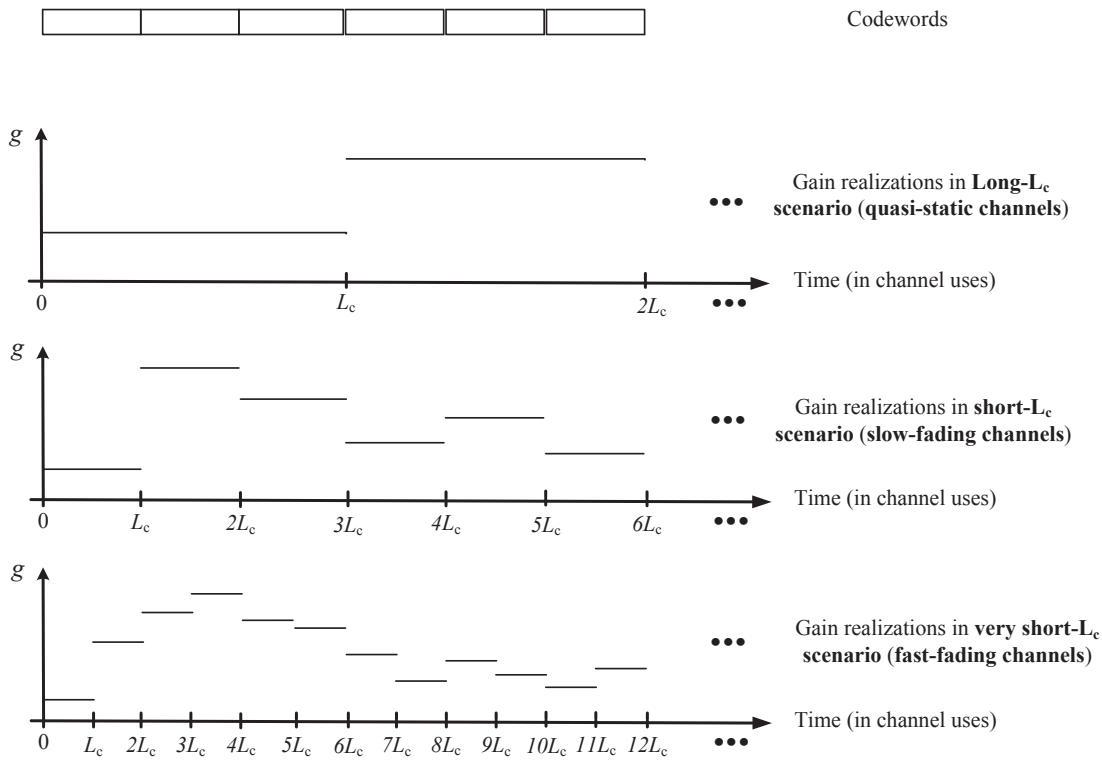
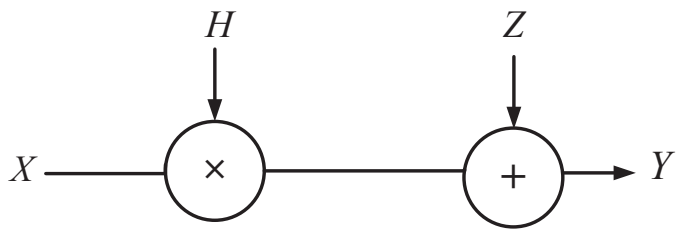
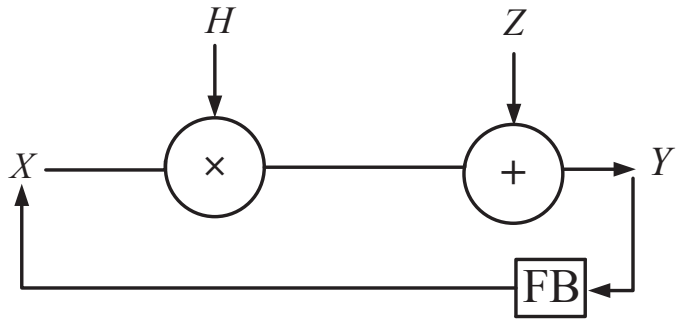


Figure 1.2: An illustration of different fading models considered throughout the thesis.



(a): Open-loop communication



(b): Closed-loop communication

Figure 1.3: (a): Open-loop communication, (b): closed-loop communication setup. The box FB represents the feedback process at the receiver.

On the other hand, as shown in, e.g., [5, 6, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25, 26, 35][2], having channel state information at the transmitter (CSIT), it is possible to improve the data transmission efficiency via updating the transmission parameters relative to the channel quality. Such a data transmission approach that, along with the CSIR, exploits the CSIT is named as a *closed-loop communication system*. Performance of the closed-loop systems depends on the mechanism conveying the channel state information (CSI) from the receiver to the transmitter[3]. Therefore, as illustrated in Fig. 1.3, a closed-loop model requires to establish a backward communication link providing the partial CSI at the transmitter. The more the CSIT is, the better system performance is achieved, because the communication parameters can be adapted based on the channel condition. Therefore, it is desired to provide the transmitter with as much as possible CSI, which in the asymptotic case leads to perfect CSIT. However, due to, e.g., limited feedback resources, implementation complexity/delay and the other users' interference constraints, it is practically difficult to provide the full CSIT. Thus, the communication setups are designed based on *partial* CSIT, where only a rough representation of the CSI is fed back to the transmitter. Along with interference-avoiding signals, which only indicate the presence of the other users [36, 37, 38], there are two main approaches to provide the partial CSI at the transmitter:

- Quantized CSI: Implementing a quantized CSI feedback scheme, the receiver provides the transmitter with some rough measure of the channel gain before transmission, and the transmitter adjusts its rate, power, etc. according to this imperfect information [22, 27, 28, 29, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59]. Rough CSI is normally produced by channel gain quantization at the receiver where the set of all possible channel gains is partitioned into a number of non-overlapping regions. The instantaneous channel gain being in a region, its representing symbol is sent back and the transmitter selects the codewords transmission parameters such that the system total performance is optimized. Quantized CSI is often referred to as *one-shot* feedback approach, as the whole partial CSI is delivered to the transmitter in one slot. In this way, the energy compression techniques which use, e.g., discrete cosine transform (DCT) and quantization for feedback compression in the frequency-domain of OFDM systems [27, 39, 60, 61, 62, 63, 64, 65] can be considered as a type of CSI quantization models.

- Automatic repeat request (ARQ): ARQ is a well-established approach aiming towards high throughput reliable wireless communication [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94]. Utilizing both forward error correction and error detection, ARQ techniques reduce the data outage probability and/or increase

[2]Due to the large number of papers dealing with partial CSI, it is not possible to mention all related works here. We apologize to the authors whose papers we have not included in our list and refer the readers to the references in the cited works.

[3]Throughout the thesis, we consider the frequency division duplexing (FDD) systems where the channel correlation between the forward and backward links is negligible.

the throughput by retransmitting the data which has experienced *bad* channel conditions; using ARQ, the transmitter considers some initial transmission rate and power with no pre-knowledge about the channel quality. Then, with the help of ARQ, the decoding status at the receiver will be reported back to the transmitter via acknowledgement/non-acknowledgement (ACK/NACK) feedback bits. Based on the received feedback, it is decided by the transmitter whether to retransmit the same (or an auxiliary) data or to move on to the next codeword. Thus, the ARQ is a *sequential* feedback approach as the transmitter gets a finer and finer knowledge of the channel in the successive time slots. ARQ is a technique already provided in many wireless protocols, e.g., IEEE 802.11n [95] and IEEE 802.16e [96].

The quantized CSI and the ARQ schemes are discussed in the following. Also, it is interesting to note that, as seen in the sequel, these two methods can be merged together providing a unique channel quality information feedback technique [17, 97]. Finally, as all results are obtained under the assumption of perfect receiver channel quality information, in the following, the abbreviation CSI is only used for the transmitter channel state information.

1.4 Quantized CSI feedback

In this section, we present the basics for studying the performance of communication setups utilizing quantized CSI. Among our own works, [30, 49, 50, 60, 98, 99, 100, 101, 102, 103] deal with different aspects of the CSI quantization; the details are presented in Section 1.7.

Implementing a quantized CSI feedback approach with N quantization regions, a deterministic mapping function (quantizer)

$$C(g) = n, \text{ if } g \in A_n = [\tilde{g}_{n-1}, \tilde{g}_n),\ n = 1, \ldots, N,\ \tilde{g}_0 = 0, \tilde{g}_N = \infty \tag{1.2}$$

is implemented by the receiver which partitions the nonnegative real line into N non-overlapping quantization regions A_n with quantization boundaries $\tilde{g}_n, n = 0, \ldots, N$. Then, if the channel realization falls into the n-th quantization region, i.e., $g \in A_n = [\tilde{g}_{n-1}, \tilde{g}_n)$, the quantization index n is sent back to the transmitter, where the transmission rate and power are selected based on the received CSI. Note that the transmitter has no CSI except the region in which the channel gain falls. Also, the feedback rate is given by $\log_2 N$ bit-per-slot (bps). Finally, denoting the gain cumulative distribution function (cdf) by $F_G(g)$, we define $p_n = \Pr(g \in A_n) = \int_{\tilde{g}_{n-1}}^{\tilde{g}_n} f_G(g)\mathrm{d}g = F_G(\tilde{g}_n) - F_G(\tilde{g}_{n-1})$ as the probability of the gain belonging to A_n.

Given that the gain realization falls in the n-th quantization region A_n, defined in (1.2), the data is transmitted with rate $R_n = \log(1 + g_n^* T_n)$ nats-per-channel-use (npcu)[4].

[4] As mentioned before, the results are given for sufficiently long codewords where the maximum achievable rate is given by $\log(1 + x)$ with x representing the received SNR. A nat is a unit of information, based on the natural logarithm [13, 14, 97, 104]. The results are presented in natural logarithm basis, while they can be mapped to the bit unit if the logarithmic terms are presented in base 2.

Here, g_n^* is an auxiliary variable, one-to-one related with rate R_n, which simplifies the equations (Thus, we may use R_n and g_n^* interchangeably in the following discussions). These parameters can be interpreted as fixed values estimated by the transmitter if $g \in A_n$. Note that, as the gain realization is in the region $A_n = [\tilde{g}_{n-1}, \tilde{g}_n)$, the optimal value of the auxiliary variable g_n^* must be within this region as well, i.e., $g_n^* \in A_n$. Finally, T_n is the power considered for the case with $g \in A_n$.

If the gain instantaneous realization supports the rate, i.e., $g \geq g_n^*$, the data is successfully decoded, otherwise outage occurs. Therefore, the probability of successful decoding in each region is

$$d_n = \Pr\left(\text{Successful decoding} | g \in A_n\right) = \frac{F_G(\tilde{g}_n) - F_G(g_n^*)}{p_n}, \tag{1.3}$$

and the channel average rate [12, 13, 22], also called the expected rate, is obtained by[5]

$$\hat{R}^{\text{QCSI}} = \sum_{n=1}^{N} p_n d_n R_n = \sum_{n=1}^{N} \left(F_G(\tilde{g}_n) - F_G(g_n^*)\right) \log(1 + g_n^* T_n), \tag{1.4}$$

which is the expectation of the achievable rates for different channel conditions. Moreover, the outage probability is found as

$$\Pr(\text{Outage})^{\text{QCSI}} = \sum_{n=1}^{N} p_n \left(1 - d_n\right) = \sum_{n=1}^{N} \Big(F_G(g_n^*) - F_G(\tilde{g}_{n-1})\Big). \tag{1.5}$$

Finally, the average transmission power is simply found as

$$\hat{\Phi}^{\text{QCSI}} = \sum_{n=1}^{N} p_n T_n. \tag{1.6}$$

In this perspective, considering T as the transmission power constraint, the power-limited average rate optimization problem can be stated as

$$\begin{aligned} \hat{R}^{\text{QCSI,max}} = \max_{\forall g_n^*, \tilde{g}_n, T_n} \; & \textstyle\sum_{n=1}^{N} \Big(F_G(\tilde{g}_n) - F_G(g_n^*)\Big) \log(1 + g_n^* T_n) \\ \text{s.t.} \quad & \textstyle\sum_{n=1}^{N} p_n T_n \leq T, \end{aligned} \tag{1.7}$$

which, based on the power allocation strategy and the fading distribution, can be solved numerically or analytically.

Considering the power-limited average rate maximization, the same procedure as in [13, 22] can be used to show that in the optimal case we have $g_n^* = \tilde{g}_{n-1}, n > 1$. This optimality condition, which is independent of the power allocation strategy, is demonstrated in Fig. 1.4 more clearly. This is an intuitive result, meaning that to maximize the average rate in power-limited communication setups utilizing quantized CSI feedback, in each quantization region except the first one, the rate is chosen equal to its worst case, corresponding to the lowest gain in the region. In this way, the outage occurs if and only if (iff) $g < g_1^*$ (please see Fig. 1.4). Thus, the outage probability is obtained by

[5]For more detailed definition of performance metrics, please see Section 1.6.

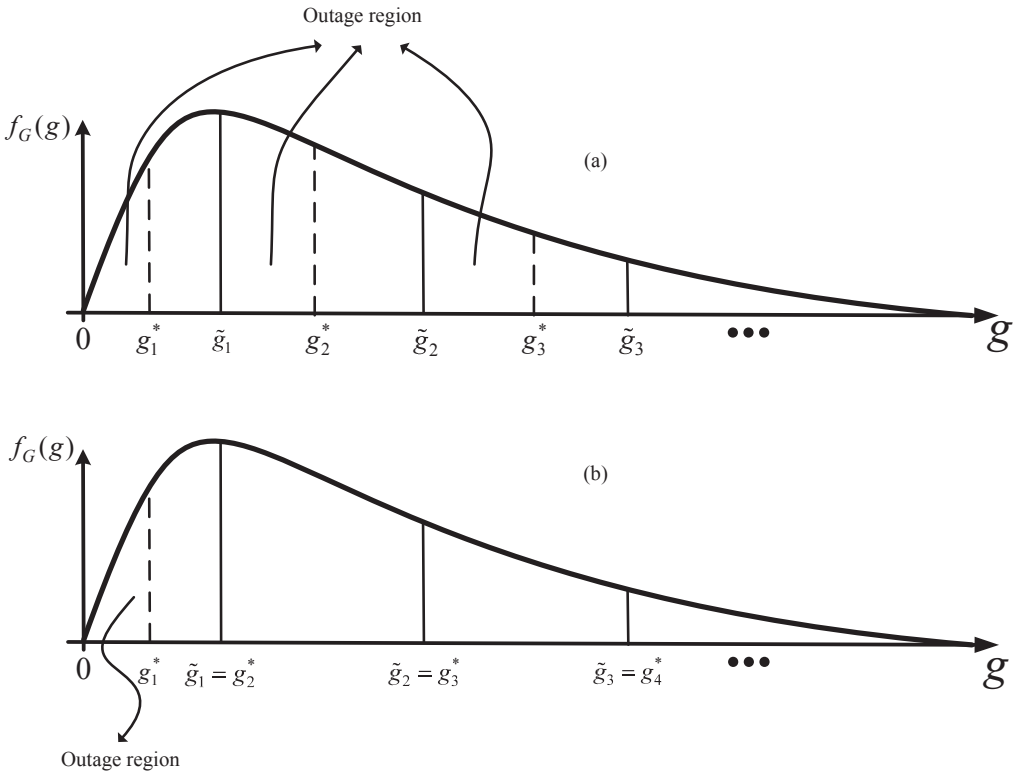


Figure 1.4: (a): Non-optimal and (b): optimal reconstruction points $g_n^*, n = 1, \ldots, N$, in the quantized CSI-based approach.

$$\Pr(\text{Outage})^{\text{QCSI}} = F_G(g_1^*), \tag{1.8}$$

and the average rate is found as

$$\hat{R}^{\text{QCSI}} = \sum_{n=1}^{N} \beta_n \log(1 + g_n^* T_n), \tag{1.9}$$

where $\beta_n = F_G(g_{n+1}^*) - F_G(g_n^*)$. Note that $\beta_n = p_n, n \neq 1$ (please see Fig. 1.4 as well). In this way, the power-limited average rate maximization problem (1.7) is rephrased as

$$\begin{aligned} \hat{R}^{\text{QCSI,max}} = \max_{\forall g_n^*, T_n} & \textstyle\sum_{n=1}^{N} \beta_n \log(1 + g_n^* T_n), \\ \text{s.t.} \quad & \textstyle\sum_{n=1}^{N} p_n T_n \leq T. \end{aligned} \tag{1.10}$$

Transmission power constraints: Based on the transmitter power adaptation capabilities, there may be different power constraints; due to, e.g., hardware or complexity limitations, there are cases where, independently of the feedback index, the power allocated to each codeword can not exceed a maximum value T. In this case, as the achievable rate of AWGN channels is an increasing function of the SNR [13, 14, 17, 22, 51, 56, 57, 85, 86, 105, 106], the optimal powers maximizing the average rate are obtained

by $T_n = T, \forall n$. This constraint is normally called *short-term*, *uniform* or *peak* power allocation [13, 14, 17, 22, 51, 56, 57, 85, 86].

Under the more relaxed *long-term*, also called *adaptive*, power allocation, the transmitter can adapt the power based on the channel conditions such that $\hat{\Phi} \leq T$. In this case, the optimal powers maximizing the average rate can be found based on (1.10) and a Lagrange multiplier function $\Omega = \hat{R}^{\text{QCSI}} - \lambda\hat{\Phi}^{\text{QCSI}}$ leading to the following water-filling [104, chapter 9.4] equation

$$\frac{\partial\Omega}{\partial T_n} = 0 \Rightarrow T_n = \left\lceil \frac{\beta_n}{\lambda p_n} - \frac{1}{g_n^*} \right\rceil^+. \tag{1.11}$$

Here, λ is the Lagrange multiplier satisfying $\hat{\Phi}^{\text{QCSI}} = T$ constraint and $\lceil x \rceil^+ \doteq \max(0, x)$. Intuitively, using long-term power allocation the power is not wasted on *weak* channel realizations and the saved power is spent on *strong* gain realizations. Therefore, it is obvious that, in comparison to the short-term power allocation, the long-term power allocation results in higher average rates. However, as noticed in many reports, the average rate increment is insignificant particularly at high SNRs.

1.4.1 Two extreme cases

It is interesting to determine the results under the two extreme conditions of full and no transmitter CSI. Having full knowledge, i.e., letting $N \to \infty$, (1.9) is rephrased as

$$\hat{R}^{\infty} = \int_0^{\infty} f_G(g) \log\big(1 + gT(g)\big) \mathrm{d}g, \tag{1.12}$$

where $T(g)$ is the power allocation function optimally determined based on the power constraint. For the short-term power constraint we have

$$\hat{R}^{\infty} = \int_0^{\infty} f_G(g) \log\left(1 + gT\right) \mathrm{d}g, \tag{1.13}$$

which has the same value as the channel capacity with perfect CSI at both communication sides and fixed transmission power.

Under the long-term power constraint, on the other hand, (1.9) is simplified to

$$\hat{R}^{\infty} = \int_{\lambda}^{\infty} \log(\frac{g}{\lambda}) f_G(g) \mathrm{d}g \tag{1.14}$$

where $\frac{1}{\lambda}$ is the water level satisfying $\int_{\lambda}^{\infty} (\frac{1}{\lambda} - \frac{1}{g}) f_G(g) \mathrm{d}g = T$. Finally, note that under the full knowledge assumption and with transmission rates limited to the maximum achievable rates, the transmitted codewords are always decoded successfully and the outage probability tends to zero.

On the other hand, with no information about the channel realization g, it is selected as some fixed value g^* and data transmission is done at rate $R = \log(1 + g^*T)$. The data

is successfully decoded iff $g \geq g^*$. Consequently, the maximum power-limited average rate is obtained by

$$\hat{R}^{\text{No,max}} = \max_{g^* \geq 0} \left\{ \left(1 - F_G(g^*) \right) \log(1 + g^* T) \right\} \tag{1.15}$$

which can be solved numerically or analytically. For instance, consider Rayleigh fading conditions where the fading coefficient follows $h \sim \mathcal{CN}(0, \frac{1}{\mu})$ and, as a result, we have $f_G(g) = \mu^{-\mu g}, g \geq 0$. In this case, the maximum average rate is found as

$$\hat{R}^{\text{No}} = \Lambda(\frac{T}{\mu}) e^{-\mu \frac{e^{\Lambda(\frac{T}{\mu})} - 1}{T}}, \tag{1.16}$$

in which $\Lambda(.)$ is the Lambert W function defined as the solution to $xe^x = y$ [14]. Also, since the data is lost if the instantaneous channel realization is less than the considered fixed value g^*, the outage probability under no knowledge assumption is

$$\Pr(\text{Outage})^{\text{No}} = F_G(g^*) = 1 - e^{-\mu g^*}, \tag{1.17}$$

where the last equality is for the Rayleigh fading channels. Finally, note that, considering $f_G(g) = \mu^{-\mu g}, g \geq 0$, (1.13) is rephrased as

$$\hat{R}^{\infty} = \int_0^{\infty} \mu e^{-\mu x} \log(1 + Tx) \mathrm{d}x = -e^{\frac{\mu}{T}} \mathrm{Ei}(-\frac{\mu}{T}),$$

with $\mathrm{Ei}(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} \mathrm{d}t$ being the exponential integral function.

In order to study the average rate optimization problem in more detail, the readers are referred to [22], where the Karush-Kuhn-Tucker (KKT) condition is derived. Fig. 1.5 compares the performance of the quantized CSI techniques with the ones in the cases utilizing full and no CSI feedback. As demonstrated in the figure, considerable performance improvement can be achieved even with feedback rates as low as 1 bps. Also, in harmony with the literature, adaptive power allocation improves the data transmission efficiency at low SNRs.

1.4.2 Discussions

To close the section, it is interesting to explain some of the possible extensions of the quantized CSI approach as follows.

Multi-layer transmission approach: Multi-layer transmission (MLT) is a well-known approach to increase the throughput in the presence or absence of quantized CSI feedback [14, 22, 107, 108, 109]. The main idea behind the MLT is to adopt the multi-user broadcast superposition code in single-user channels. Let K be the number of transmission layers. The channel quantization is done in the same way as described before. The difference with the single-layer transmission (SLT) approach is that, instead of considering a single g_n^*, K fixed values $g_n^*(k)$, $k = 1, \ldots, K$, are considered where $g_n^*(k-1) \leq g_n^*(k)$. In this

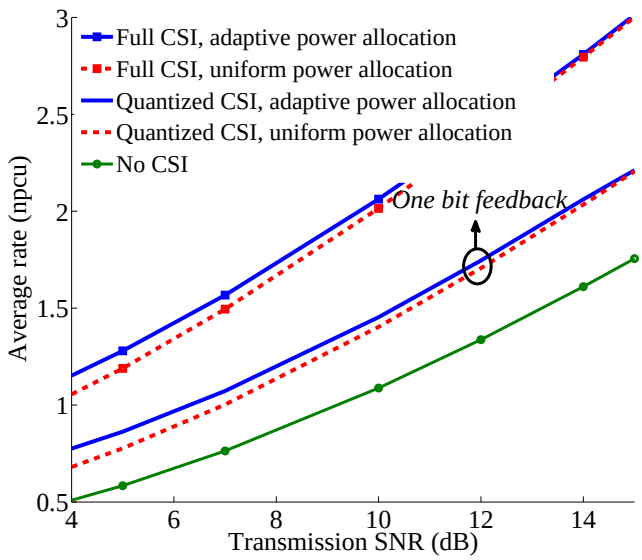


Figure 1.5: Average rate vs the transmission SNR with different amount of CSI available at the transmitter, Rayleigh fading channel, $\mu = 1$.

way, receiving the quantization region n, the data is transmitted via superposition of K codewords with powers $T_n(k)$ and rates

$$R_n(k) = \log\left(1 + \frac{g_n^*(k)T_n(k)}{1 + g_n^*(k)\sum_{j=k+1}^{K} T_n(j)}\right), \; k = 1, \ldots, K. \tag{1.18}$$

At the receiver, the data is decoded using a successive decoding procedure where, decoding the k-th layer, all undecoded layers $j = k+1, \ldots, K$, are added to the noise floor. Hence, the code of the k-th layer is successfully decoded and subtracted from the provided signal if $g \geq g_n^*(k)$. Otherwise, the decoder gives up declaring an outage. Thus, the average rate and the transmission power are obtained as

$$\hat{R}^{\mathrm{MLT}} = \sum_{n=1}^{N}\sum_{k=1}^{K} R_n(k)\Pr\left(g \geq g_n^*(k) \,\&\, g \in A_n\right) \tag{1.19}$$

and $\hat{\Phi}^{\mathrm{MLT}} = \sum_{n=1}^{N}\sum_{k=1}^{K} p_n T_n(k)$, respectively, which change (1.10) correspondingly.

Theoretically, MLT outperforms the SLT in terms of average rate, particularly for low feedback rates [14, 22, 107, 108, 109]. In practice, however, MLT suffers from error propagation problems; depending on the gain realization, it may happen that only some part of the data can be decoded at the receivers which leads to extra complications in the upper layers in the network hierarchy (In these applications, ARQ schemes can be combined with MLT). Further, MLT is not tolerable in all applications but only in successive refinement systems that produce a coarse version of the information and gradually improve it as more information is received. Also, although the average rate increases by increasing the number of layers, the increment is negligible for many fading pdfs [14]. This is specifically because of the *self-interference* created in the codewords where decoding a layer all undecoded layers play the role of additive interference.

On the effect of an unreliable feedback link: Throughout the section, we supposed the feedback signals to be received by the transmitter error-free. However, in wireless networks the feedback signals reach the transmitter through a communication link experiencing different levels of noise and fading. Hence, it is possible to receive erroneous signals at the transmitter which, if not handled suitably, can degrade the system performance severely and make it even worse than an open-loop system. Therefore, an interesting extension of the quantized CSI schemes is to consider the effect of feedback channel properties and study the system performance in the presence of erroneous feedback signals. This problem has been studied by, e.g., [35, 41, 51, 57] and by us in [49].

Exploiting the temporal correlation: Considering the block-fading channel, the fading coefficients are normally assumed to be random variables that remain constant over time intervals of fixed duration and vary across successive blocks in an i.i.d. manner. This is a useful model particularly for analytical performance analysis. For the limited-feedback schemes, however, we can extend the fading model to the *temporally-correlated* block-fading channels and exploit the channel temporal correlations for feedback compression [27, 28, 29, 30, 31, 32, 33]. There are a number of methods, such as feedback subsampling [26, 27] and time differential information [32, 33], to exploit the channel temporal dependencies. Time differential information approach refers to the technique reporting the difference between the partial CSI of successive blocks [32, 33]. Using feedback subsampling, which is explicitly explained in paper B appended to the thesis, the CSI is fed back in specific time slots and in the other blocks it is estimated via, e.g., minimum mean square error (MMSE) estimators. Moreover, the channel temporal dependencies can be utilized to dynamically adjust the quantization boundaries, e.g., [30], and study the effect of delayed feedback on the system performance [26, 110, 111].

It is worth noting that there are different transform coding approaches for exploiting frequency-domain correlations [27, 39, 60, 61, 62, 63, 64, 65]. These works, which are normally considered for the OFDM setups, compress the feedback signal by implementation of different energy compression techniques such as the DCT.

The results of the section were presented for the single-user single-antenna channels. However, there are many papers dealing with CSI quantization in the multiple-input and multiple-output (MIMO)/network MIMO and cooperative communication setups, e.g., [28, 29, 58, 112, 113, 114]. In these works, the random vector quantization approach is normally considered, the quantization error is modeled by an additive Gaussian noise and the goal is to design, e.g., the beamforming scheme optimizing the system performance.

1.5 ARQ feedback

Along with the quantized CSI, automatic repeat request is one of the most well-known limited-feedback approaches increasing the data transmission efficiency and reliability [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86]. It is a technique already provided in most wireless protocols. Therefore, it needs no additional closed-loop design which introduces it as a cost- and complexity-efficient approach. There are different ARQ schemes such as *stop-and-wait*

[115], *go-back-N* [116] or *selective-repeat* [117] developed by the researchers during the last decades. The main idea of the ARQ approaches is to increase the transmission reliability by correcting erroneous data misdecoded by the receiver. For this reason, a code with good error-detecting capability is used by the transmitter and then waits for an acknowledgement from the receiver. A positive acknowledgement from the receiver indicates that the data has been successfully decoded. Therefore, the transmitter moves into the next codeword. On the other hand, a negative acknowledgement from the receiver signals that the received data has been decoded imperfectly and so it should be corrected by the transmitter. Therefore, the same or a new auxiliary codeword is retransmitted by the transmitter. Retransmissions continue until the data is correctly decoded or the maximum allowable retransmission rounds are used.

Throughout the thesis, we concentrate on different ARQ protocols; as the discussions of this chapter are presented for single-input and single-output (SISO) setups, we concentrate on the following protocols:

- Basic ARQ: The transmitter keeps sending the same codeword and the receiver attempts decoding by using only the most recently received codeword. This loop continues until the ACK is declared by the receiver or the maximum retransmission rounds are used.

- Repetition time diversity (RTD): The transmitter sends the same codeword and the receiver performs maximum ratio combining of all the received codewords, thus realizing repetition time diversity. This scheme, which belongs to the *diversity combining* category of hybrid ARQ (HARQ) protocols, is also known as Chase combining [118].

- Incremental redundancy (INR): The INR belongs to the category of *code combining* protocols [12, 13, 14, 16, 17, 68, 74]. Here, a codeword is sent with an aggressive rate in the first round. Then, if the receiver cannot decode the initial codeword, further parity bits are sent in the next retransmission rounds, and in each round the receiver tries to decode the data based on all received signals.

In paper F, we also discuss space-time code (STC)-based MIMO-ARQ schemes.

In the following, we review the basic concepts of the ARQ protocols. Here, we study the problem of power-limited long-term throughput/outage probability optimization for the quasi-static channels. Our own work on ARQ schemes is found in [25, 34, 85, 119, 120, 121, 122, 123], where we study the performance of the ARQ-based systems from different perspectives. Moreover, in [12, 13, 26, 86, 97, 109, 124] we demonstrate different comparisons or combinations of the quantized CSI and the ARQ protocols. More detailed descriptions of our developed works are presented in Section 1.7.

Consider a maximum of M retransmission rounds, i.e., the data is (re)transmitted a maximum of $M+1$ rounds. Moreover, assume that Q information nats are transmitted in each *packet* transmission where a packet is defined as the transmission of a codeword along with all its possible retransmission rounds. If the data is successfully decoded at any

(re)transmission round, all the Q nats are received by the receiver. Hence, the expected number of received information nats is found as

$$E\{Q(g)\} = Q\left(1 - \Pr(\text{Outage})\right) = Q\left(1 - \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})\right) \tag{1.20}$$

where $E\{.\}$ represents the expectation operator, S_m is the event that the data is correctly decoded at the end of the m-th round (and not before) and $\bar{V}$ denotes the complement of the event V.

If the message is correctly decoded at the end of the m-th (re)transmission round (and not before), the total number of channel uses is $l_{(m)} = \sum_{n=1}^{m} l_n$ where l_n denotes the length of the codeword sent in the n-th (re)transmission round. Also, the total number of channel uses is $l_{(M+1)} = \sum_{n=1}^{M+1} l_n$ if an outage occurs, where all possible retransmissions are used. Therefore, the expected number of channel uses within a packet transmission period is

$$E\{\tau(g)\} = \sum_{m=1}^{M+1} \left(\sum_{n=1}^{m} l_n\right) \Pr(S_m) + \left(\sum_{n=1}^{M+1} l_n\right) \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}). \tag{1.21}$$

In this way, from (1.20), (1.21) and as the equivalent data rate at the end of the m-th (re)transmission round is

$$R_{(m)} = \frac{Q}{\sum_{n=1}^{m} l_n}, \; R_{(0)} \doteq \infty, \tag{1.22}$$

the long-term throughput, i.e., the ratio of the successfully decoded information nats and the expected channel uses [12, 13, 14, 17, 68, 125], is found as[6]

$$\hat{\eta} = \frac{E\{Q(g)\}}{E\{\tau(g)\}} = \frac{1 - \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})}{\sum_{m=1}^{M+1} \frac{\Pr(S_m)}{R_{(m)}} + \frac{\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})}{R_{(M+1)}}}. \tag{1.23}$$

Provided that the data (re)transmission terminates at the end of the m-th round (and not before), the total consumed energy is $\xi_{(m)} = \sum_{n=1}^{m} T_n l_n$. Therefore, the expected energy consumed within a packet transmission period is obtained by

$$\begin{aligned} E\{\xi(g)\} &= \textstyle\sum_{m=1}^{M+1} \left(\sum_{n=1}^{m} T_n l_n\right) \Pr(S_m) + \left(\sum_{n=1}^{M+1} l_n T_n\right) \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}) \\ &\overset{(a)}{=} Q \textstyle\sum_{m=1}^{M+1} \left(\sum_{n=1}^{m} T_n \left(\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}\right)\right) \Pr(S_m) \\ &\quad + Q \left(\textstyle\sum_{n=1}^{M+1} T_n \left(\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}\right)\right) \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}), \end{aligned} \tag{1.24}$$

where (a) is due to the fact that $l_m = \frac{Q}{R_{(m)}} - \frac{Q}{R_{(m-1)}}$. Finally, from (1.21), (1.24), $R_{(m)} =$

[6]For more detailed definition of long-term throughput and average power, please see Section 1.6.

$\frac{Q}{\sum_{n=1}^{m} l_n}$ and some manipulations, the average transmission power is rephrased as

$$\hat{T} = \frac{E\{\xi(g)\}}{E\{\tau(g)\}} = \frac{\sum\limits_{m=1}^{M+1} T_m \left(\frac{1}{R_{(m)}} - \frac{1}{R_{(m-1)}}\right)\left(1 - \sum\limits_{n=1}^{m-1} \Pr(S_n)\right)}{\sum\limits_{m=1}^{M+1} \frac{\Pr(S_m)}{R_{(m)}} + \frac{\Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})}{R_{(M+1)}}}. \tag{1.25}$$

Therefore, the power-limited long-term throughput optimization problem can be expressed as

$$\hat{\eta}^{\text{ARQ,max}} = \max_{\forall T_m, R_{(m)}} \frac{1 - \Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})}{\sum_{m=1}^{M+1} \frac{\Pr(S_m)}{R_{(m)}} + \frac{\Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})}{R_{(M+1)}}} \tag{1.26}$$

$$\text{s.t.} \quad \frac{\sum\limits_{m=1}^{M+1} T_m \left(\frac{1}{R_{(m)}} - \frac{1}{R_{(m-1)}}\right)\left(1 - \sum\limits_{n=1}^{m-1} \Pr(S_n)\right)}{\sum\limits_{m=1}^{M+1} \frac{\Pr(S_m)}{R_{(m)}} + \frac{\Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})}{R_{(M+1)}}} \leq T, \tag{1.27}$$

where T denotes the average power constraint.

Notice that with uniform power allocation, the power constraint (1.27) simplifies to $T_m = T' \leq T$. Then, as the achievable rate of the AWGN channel is an increasing function of the transmission power [13, 14, 17, 22, 51, 56, 57, 85, 86, 105, 106], maximizing the achievable rate implies $T_m = T, \forall m$. Also, it is interesting to note that up to now all equations are general, in the sense that they are independent of the fading pdf and the ARQ protocol. Finally, from (1.20)-(1.27) it follows that the only difference between different ARQ protocols is in the probability terms $\Pr(S_m)$. Moreover, to find the power-limited throughput of different ARQ protocols, it is only required to determine their corresponding probability terms in (1.23) and (1.25).

***Remark 1**:* For fixed-length coding ARQ schemes (where all (re)transmissions have the same number of channel uses), the maximum power-limited long-term throughput is obtained by

$$\hat{\eta}^{\text{fixed-length ARQ,max}} = \max_{\forall T_m, R} \frac{R(1 - \Pr(\bar{S}_1,\ldots,\bar{S}_{M+1}))}{\sum_{m=1}^{M+1} m \Pr(S_m) + (M+1)\Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})} \tag{1.28}$$

$$\text{s.t.} \quad \frac{\sum\limits_{m=1}^{M+1} T_m \left(1 - \sum_{n=1}^{m-1} \Pr(S_n)\right)}{\sum_{m=1}^{M+1} m \Pr(S_m) + (M+1)\Pr(\bar{S}_1,\ldots,\bar{S}_{M+1})} \leq T, \tag{1.29}$$

where $R = \frac{Q}{L}$ is the initial codeword rate and L is the length of the codewords. This is because using $l_m = L$, $\forall m$, we have $R_{(m)} = \frac{Q}{mL} = \frac{R}{m}$ which rephrases (1.23) and (1.25) as in (1.28) and (1.29), respectively.

Finally, note that to study the problem of power-limited outage probability minimization it is only required to replace (1.28) with the outage probability. In the sequel, the general equations (1.23) and (1.25) are specialized for different ARQ protocols.

1.5.1 RTD protocols

Utilizing the RTD HARQ, the same codeword is scaled and (re)transmitted in each (re)transmission round and the receiver performs maximum ratio combining of the received signals. This process effectively increases the received SNR to $g\sum_{n=1}^{m} T_n$ and reduces the equivalent data rate to $R_{(m)} = \frac{R}{m}$ in the m-th round. Define $J_{(m)} \doteq \frac{1}{m}\log(1+g\sum_{n=1}^{m} T_n)$ as the instantaneous mutual information and $\Upsilon_m \doteq \{J_{(m)} \geq R_{(m)}\}$ as the event that the instantaneous mutual information exceeds the equivalent data rate at the m-th (re)transmission round. The data is successfully decoded at the m-th retransmission round (and not before) if 1) the receiver has not decoded the message in the previous (re)transmissions, i.e., $J_{(n)} < \frac{R}{n}\ \forall n < m$, and 2) using the m-th retransmission round it can decode the information, that is, $J_{(m)} \geq \frac{R}{m}$. Then, as $\Upsilon_m \subset \Upsilon_n, n \leq m$, we have

$$\begin{aligned}
\Pr(S_m) &= \Pr(\bar{\Upsilon}_1, \ldots, \bar{\Upsilon}_{m-1}, \Upsilon_m) \\
&= \Pr\left(\log(1+g\textstyle\sum_{n=1}^{m-1} T_n) < R \leq \log(1+g\sum_{n=1}^{m} T_n)\right) \\
&= F_G(\tfrac{e^R-1}{\sum_{n=1}^{m-1} T_n}) - F_G(\tfrac{e^R-1}{\sum_{n=1}^{m} T_n}), \\
\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}) &= \Pr\left(\log(1+g\textstyle\sum_{n=1}^{M+1} T_n) < R\right) = F_G(\tfrac{e^R-1}{\sum_{n=1}^{M+1} T_n}).
\end{aligned} \tag{1.30}$$

Note that in (1.30) we have used the fact that with an equivalent SNR x the maximum decodable data rate is $\frac{1}{m}\log(1+x)$ if a codeword is repeated m times. Also, $\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})$ represents the outage probability, i.e., the probability that the data is lost while all retransmission rounds have been used. Moreover, using uniform power allocation $T_m = T$, $\forall m$, (1.30) is rephrased as

$$\begin{aligned}
\Pr(S_m) &= F_G(\tfrac{e^R-1}{(m-1)T}) - F_G(\tfrac{e^R-1}{mT}), \\
\Pr(\text{Outage}) &= F_G(\tfrac{e^R-1}{(M+1)T}).
\end{aligned} \tag{1.31}$$

Using (1.28), (1.29), (1.30) and some manipulations, the long-term throughput and the average power of the RTD protocol are found as

$$\hat{\eta}^{\text{RTD}} = \frac{R\left(1 - F_G(\frac{e^R-1}{\sum_{n=1}^{M+1} T_n})\right)}{1+\sum_{m=1}^{M} F_G(\frac{e^R-1}{\sum_{n=1}^{m} T_n})} \tag{1.32}$$

and

$$\hat{T}^{\text{RTD}} = \frac{T_1 + \sum_{m=2}^{M+1} T_m F_G(\frac{e^R-1}{\sum_{n=1}^{m-1} T_n})}{1+\sum_{m=1}^{M} F_G(\frac{e^R-1}{\sum_{n=1}^{m} T_n})}, \tag{1.33}$$

respectively. Thus, the power-limited long-term throughput optimization problem of the

RTD protocol can be represented as

$$\hat{\eta}^{\text{RTD,max}} = \max_{R,T_1,\ldots,T_{M+1}} \frac{R\left(1-F_G(\frac{e^R-1}{\sum_{n=1}^{M+1} T_n})\right)}{1+\sum_{m=1}^{M} F_G(\frac{e^R-1}{\sum_{n=1}^{m} T_n})} \quad \text{s.t.} \quad \frac{T_1+\sum_{m=2}^{M+1} T_m F_G(\frac{e^R-1}{\sum_{n=1}^{m-1} T_n})}{1+\sum_{m=1}^{M} F_G(\frac{e^R-1}{\sum_{n=1}^{m} T_n})} \leq T, \tag{1.34}$$

which is a non-convex problem [14, 17, 85] and, depending on the fading pdf and the number of retransmissions, may need to be solved numerically.

1.5.2 INR protocols

Using INR, new codewords are (re)transmitted in the (re)transmissions and in each round the receiver combines all signals received up to the end of that round. Following the discussions in [104, chapter 15], [126, chapter 7], [127], the probability terms $\Pr(S_m)$ and $\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})$ are obtained by

$$\begin{aligned} \Pr(S_m) &= \Pr\left(R_{(m)} \leq \frac{\sum_{n=1}^{m} l_n \log(1+gT_n)}{\sum_{j=1}^{m} l_j} \cap R_{(m-1)} > \frac{\sum_{n=1}^{m-1} l_n \log(1+gT_n)}{\sum_{j=1}^{m-1} l_j}\right) \\ \Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}) &= \Pr\left(R_{(M+1)} > \frac{\sum_{n=1}^{M+1} l_n \log(1+gT_n)}{\sum_{j=1}^{M+1} l_j}\right), \end{aligned} \tag{1.35}$$

for INR. Here, (1.35) follows from the fact that using m different codewords of length l_n and power T_n, $n = 1, \ldots, m$, the maximum decodable information rate is $U_m = \sum_{n=1}^{m} \frac{l_n}{\sum_{j=1}^{m} l_j} \log(1 + gT_n)$. Note that, based on (1.22), we have

$$\frac{l_n}{\sum_{j=1}^{m} l_j} = R_{(m)} \left(\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}\right) \tag{1.36}$$

and so $\Pr(S_m)$ is found as a function of $R_{(n)}$'s. Hence, using (1.25), (1.35) and some calculations, the average INR-based transmission power is obtained by

$$\begin{aligned} \hat{T}^{\text{INR}} &= \frac{\frac{T_1}{R_{(1)}} + \sum_{n=2}^{M+1} T_n(\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}})\Theta_n}{\frac{1}{R_{(1)}} + \sum_{n=2}^{M+1} (\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}})\Theta_n}, \\ \Theta_n &\doteq \Pr(\sum_{j=1}^{n-1} (\frac{1}{R_{(j)}} - \frac{1}{R_{(j-1)}}) \log(1 + gT_j) < 1). \end{aligned} \tag{1.37}$$

Also, following (1.23) and (1.35), the long-term throughput is found as

$$\hat{\eta}^{\text{INR}} = \frac{\Pr(\sum_{n=1}^{M+1} (\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}) \log(1 + gT_n) \geq 1)}{\frac{1}{R_{(1)}} + \sum_{n=2}^{M+1} (\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}})\Theta_n}. \tag{1.38}$$

Moreover, the outage probability is given by

$$\Pr(\text{Outage})^{\text{INR}} = \Pr(\sum_{n=1}^{M+1} (\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}) \log(1 + gT_n) < 1). \tag{1.39}$$

Finally, assuming short-term power constraint, $T_m = T, \forall m$, (1.38) simplifies to

$$\hat{\eta}^{\text{INR}} = \frac{1 - F_G(\frac{e^{R_{(M+1)}}-1}{T})}{\sum_{m=1}^{M+1} \frac{F_G(\frac{e^{R_{(m-1)}}-1}{T}) - F_G(\frac{e^{R_{(m)}}-1}{T})}{R_{(m)}} + \frac{F_G(\frac{e^{R_{(M+1)}}-1}{T})}{R_{(M+1)}}} \tag{1.40}$$

and the outage probability is rephrased as

$$\Pr(\text{Outage})^{\text{INR}} = \Pr(\log(1 + gT) < R_{(M+1)}) = F_G(\frac{e^{R_{(M+1)}} - 1}{T}). \tag{1.41}$$

Variable-length INR results in high long-term throughput and low outage probability, but it also leads to high complexity [13, 14, 17]. In order to reduce the complexity, fixed-length coding INR scheme can be considered where setting $l_m = L$, $\forall m$, in (1.37)-(1.38) leads to $R_{(m)} = \frac{R}{m}$,

$$\hat{T}^{\text{INR,fixed-length}} = \frac{T_1 + \sum_{n=2}^{M+1} T_n \Theta_n}{1 + \sum_{n=2}^{M+1} \Theta_n},$$

$$\Theta_n = \Pr(\sum_{j=1}^{n-1} \log(1 + gT_j) < R), \tag{1.42}$$

and

$$\hat{\eta}^{\text{INR,fixed-length}} = \frac{R \Pr(\sum_{n=1}^{M+1} \log(1 + gT_n) \geq R)}{1 + \sum_{n=2}^{M+1} \Theta_n}, \tag{1.43}$$

where R denotes the initial codeword rate.

Considering different values of m, there is no general closed-form solution for Θ_m. Thus, depending on the fading distribution and the number of retransmissions, Θ_m may need to be calculated numerically. However, as $R_{(n)} < R_{(n-1)}, \forall n$, the function $U_m(g) = R_{(m)} \sum_{n=1}^{m} (\frac{1}{R_{(n)}} - \frac{1}{R_{(n-1)}}) \log(1 + gT_n)$ is an increasing function of g and, therefore, for a given set of $\{T_n, R_{(n)}, n = 1, \ldots, m\}$, Θ_m can be uniquely obtained via, e.g., "fsolve" function of MATLAB. However, to be more analytically trackable, several approximations have been proposed for Θ_m in the literature [12, 74, 119, 128, 129]. The following lemma demonstrates an example of such approximations.

Lemma 1: For the fixed-length INR protocol, the system performance is underestimated, i.e., the long-term throughput is lower bounded and the outage probability is upper bounded, via the following inequalities

$$\Theta_m \leq F_G(\frac{e^{\frac{R}{m}} - 1}{\sqrt[m]{\prod_{i=1}^{m} T_i}}), \forall m. \tag{1.44}$$

Proof. Considering the data transmission policy of the INR protocol, it can be easily shown that the performance of the fixed-length INR scheme is a decreasing function of Θ_m [17, 119]. In other words, the system performance is underestimated if the maximum decodable rates $U_m^{\text{fixed-length}} = \frac{1}{m}\sum_{i=1}^{m}\log(1+gT_i)$ are replaced by their corresponding lower bounds. From (1.42), we can write

$$\Theta_m = \Pr\left(U_m^{\text{fixed-length}} < \frac{R}{m}\right) = \Pr(\Psi < e^R). \tag{1.45}$$

Here, Ψ is defined as

$$\Psi \doteq \prod_{i=1}^{m}(1+gT_i) = \det(\mathbf{I}_m + \mathbf{C}) \tag{1.46}$$

with $\mathbf{I}_m$ representing the $m \times m$ identity matrix and $\mathbf{C} = [c_{i,k}]$ denoting the diagonal matrix given by

$$c_{i,k} = \begin{cases} gT_i & \text{if } i = k, i = 1, \ldots, m, \\ 0 & \text{if } i \neq k. \end{cases} \tag{1.47}$$

Using the Minkowski's inequality [130, Theorem 7.8.8] in (1.46) leads to

$$\Psi = \det(\mathbf{I}_m + \mathbf{C}) \geq (1 + \det(\mathbf{C})^{\frac{1}{m}})^m. \tag{1.48}$$

Thus, from $\det(\mathbf{C}) = g^m \prod_{i=1}^{m} T_i$, we have $\Psi \geq (1 + g\sqrt[m]{\prod_{i=1}^{m} T_i})^m$ and

$$\Pr\left(\sum_{i=1}^{m}\log(1+gT_i) < R\right) \leq \Pr\left(\left(1 + g\sqrt[m]{\prod_{i=1}^{m} T_i}\right)^m < e^R\right) = F_G\left(\frac{e^{\frac{R}{m}} - 1}{\sqrt[m]{\prod_{i=1}^{m} T_i}}\right), \tag{1.49}$$

as stated in the lemma. □

Due to properties of the Minkowski's inequality, the bounds are tight at low SNRs, which is the range of interest in adaptive power allocation schemes [12, 13, 14, 17, 74, 85] (For the simulation results and other approximations of Θ_m, please see paper G which is appended to the thesis). Finally, further discussions about the performance analysis of the INR ARQ will be presented later in papers A, C, D and F which are appended.

In general, the power-limited throughput/outage probability optimization of the ARQ protocols are non-convex problems. Also, depending on the fading pdf and the maximum number of retransmissions, there is no general closed-form solution for the optimal (re)transmission powers maximizing the throughput or minimizing the outage probability. Several discussions about the optimal retransmission powers/rates of the ARQ schemes have been presented in, e.g., [13, 14, 34, 73, 74, 85, 119]. Also, reviewing the literature, one can find different comparisons between the ARQ protocols, particularly between the RTD and the INR schemes [13, 14, 16, 17, 34, 119, 131]. The final conclusion of the

comparisons is that INR outperforms RTD from different aspects. The superiority of INR over RTD is due to the fact that a *better* code is implemented in INR, compared to RTD. Therefore, we can use the same arguments as in [13, 14, 16, 17, 119, 131] to show that INR outperforms RTD in terms of different metrics. Furthermore, as demonstrated in, e.g., [131], the gain of the INR protocol over the RTD increases with the initial transmission rate. Also, [131] has previously shown that the difference between the performance of the RTD and INR protocols decreases with the SNR variation between the retransmissions. Thus, compared to the quasi-static fading model, the gain of INR over RTD decreases in the slow- and fast-fading scenarios. Finally, the difference between the performance of these methods decreases when the transmission power decreases [34, 85, 119] and when the ARQ feedback bits become unreliable, i.e., there is some error probability for decoding the ACK/NACK feedback bits [121].

1.5.3 Basic ARQ protocols

In basic ARQ protocols with adaptive power allocation, the transmitter keeps sending scaled versions of the same codeword in the (re)transmission rounds and the receiver decodes only the most recently received signal, regardless of the previously received signals.

For a slow-fading channel (short-L_c scenario), [19] has previously shown that the transmission powers in the basic ARQ protocol should increase with the number of retransmission round if the goal is to minimize the outage probability. Moreover, as mentioned in [14], considering the quasi-static channel (long-L_c scenario) there is no use in basic ARQ if uniform power allocation is implemented. The intuition behind this is that with a fixed fading channel there is no time diversity to be exploited in the (re)transmission rounds. Therefore, sending the same codeword with no power adaptation does not increase the probability of decoding the message. The following lemma shows that, for a large range of optimization objective functions and for any feedback channel conditions, the transmission powers in the basic ARQ scheme must be increasing in every round, if the channel remains fixed within all (re)transmissions.

Lemma 2: Consider the long-L_c scenario, i.e., quasi-static fading model. In power-adaptive basic ARQ schemes the optimal transmission powers, in terms of e.g., long-term throughput or outage probability, must be increasing in every retransmission.

Proof. Using basic ARQ, the data is decodable at the m-th (re)transmission round if $\log(1 + gT_m) \geq R$ where $R = \frac{Q}{L}$ is the initial codeword rate. Therefore, given that the codeword is not decodable at the m-th round, i.e., $g < \frac{e^R-1}{T_m}$, retransmitting it with lower (or equal) power at the $(m+1)$-th round is useless as $\Pr(g < \frac{e^R-1}{T_{m+1}} | g < \frac{e^R-1}{T_m} \,\&\, T_m \geq T_{m+1}) = 1$. Therefore, to have some chance for decoding the data, we should have $T_m \leq T_{m+1}, \forall m$. Note that the lemma is presented for the outage probability and long-term throughput. However, the same argument holds for every other metric that we have checked. Also, depending on the fading pdf, the optimal power allocation rule may be in the form of $T_m = 0, m \neq M+1, T_{M+1} > 0$, in that case there is no use in basic ARQ. □

Using Lemma 2, the long-term throughput and the average transmission power for the

basic ARQ protocol in long-L_c scenario are obtained with the same equations as for the RTD scheme, e.g., (1.34), while the probability terms $\Pr(S_m)$ and $\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})$ are respectively replaced by

$$\Pr(S_m) = \Pr\left(\log(1 + gT_{m-1}) < R \leq \log(1 + gT_m)\right) = F_G\left(\frac{e^R - 1}{T_{m-1}}\right) - F_G\left(\frac{e^R - 1}{T_m}\right) \tag{1.50}$$

and

$$\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}) = \Pr\left(R > \log(1 + gT_{M+1})\right) = F_G\left(\frac{e^R - 1}{T_{M+1}}\right). \tag{1.51}$$

As less information is exploited by the basic ARQ decoder, compared to the RTD, the RTD outperforms the basic ARQ from different points of view.

1.5.4 Discussions

Some of the possible extensions of the ARQ-based systems are described as follows.

On the effect of temporal channel variations: We analyzed the performance of the ARQ protocols under the quasi-static channel assumptions (long-L_c scenario), where the channel remains fixed during all retransmissions. However, it is straightforward to extend the results to the case with a slow-fading channel, in which the channel changes in each round. In this case, while the long-term throughput, the average transmission power and the outage probability, e.g., (1.23), (1.25) and (1.39), are obtained with the same procedure as before, the probability terms $\Pr(S_m)$ and $\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})$ are replaced by

$$\Pr(S_m) = \begin{cases} \Pr\left(\log(1 + \sum_{n=1}^{m-1} g_n T_n) < R \leq \log(1 + \sum_{n=1}^{m} g_n T_n)\right) & \text{For RTD} \\ \Pr\left(\sum_{n=1}^{m-1} \log(1 + g_n T_n) < R \leq \sum_{n=1}^{m} \log(1 + g_n T_n)\right) & \text{For INR} \\ \Pr\left(\log(1 + g_n T_n) < R, \forall n < m \,\&\, \log(1 + g_m T_m) \geq R\right) & \text{For basic ARQ} \end{cases} \tag{1.52}$$

$$\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1}) = \begin{cases} \Pr\left(\log(1 + \sum_{n=1}^{M+1} g_n T_n) < R\right) & \text{For RTD} \\ \Pr\left(\sum_{n=1}^{M+1} \log(1 + g_n T_n) < R\right) & \text{For INR} \\ \Pr\left(\log(1 + g_n T_n) < R, \forall n \leq M + 1\right) & \text{For basic ARQ} \end{cases} \tag{1.53}$$

where g_m is the channel realization at the m-th round. As seen later in paper F, many qualitative conclusions derived for the ARQ protocols are valid independent of the fading model, as the arguments hold for every given probability terms $\Pr(S_m)$ and $\Pr(\bar{S}_1, \ldots, \bar{S}_{M+1})$, independent of how they are found. Moreover, paper F presents mappings between the performance of the ARQ protocols with different fading models. Finally, extension of the results to the cases with a fast-fading model (very short-L_c scenario) is addressed in paper D.

Noisy ARQ: The same as in the quantized CSI techniques, we can study the effect of feedback channel noise on the performance of the ARQ protocols. With an unreliable ARQ feedback, the data may be retransmitted while it was decoded before or the codeword (re)transmission may stop while the message has not been correctly decoded. Among the papers dealing with noisy ARQ protocols are, e.g., [76, 81, 82, 121, 132, 133, 134]. Here, it is worth noting that, as demonstrated by us in [121], the ARQ protocols are not very sensitive to feedback channel noise, when the goal is to maximize the throughput in a practical range of feedback bit error probabilities. However, the erroneous feedback signal affects the outage probability of the ARQ protocols considerably.

Combination of quantized CSI and ARQ protocols: The combination of the ARQ and quantized CSI schemes can improve the performance of the limited-feedback communication setups, e.g. [17, 97, 135]. In this case, the quantized CSI provides some rough pre-knowledge for the transmitter and then the ARQ protocols are implemented to compensate the transmitter imperfect knowledge about the channel quality. Particularly, as illustrated in paper E, there are cases where the combination of the ARQ and quantized CSI schemes can be mapped to the case utilizing only one of them. However, as paper E is appended to the thesis, we do not go into details here.

1.6 Performance metrics and data communication models

Considering delay-sensitive data transmission over a block-fading channel, there are different metrics and data communication models that have been considered in the literature. In the following, we briefly introduce these metrics and models.

1.6.1 Performance metrics

Some of the metrics that are normally considered for evaluating the system performance are listed in the following. It is worth noting that some of the metrics that are studied in this section have been used in the previous sections as well. However, for the completeness of the text, their more detailed definitions are mentioned here.

- Outage probability: As mentioned before, the outage probability is defined as the probability of the event that the message is not correctly decoded by the receiver, when the data (re)transmission stops.

- Long-term throughput: As aforementioned, the long-term throughput is defined as,

e.g., [12, 13, 14, 17, 68, 125]

$$\hat{\eta} = \frac{\text{Total number of successfully decoded nats}}{\text{Total time for sending the codewords}} = \lim_{I\to\infty} \frac{\sum_{i=1}^{I} Q_i}{\sum_{i=1}^{I} \tau_i} = \lim_{I\to\infty} \frac{\frac{1}{I}\sum_{i=1}^{I} Q_i}{\frac{1}{I}\sum_{i=1}^{I} \tau_i}$$
$$\overset{(a)}{=} \frac{\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} Q_i}{\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} \tau_i} \overset{(b)}{=} \frac{E\{Q(g)\}}{E\{\tau(g)\}}. \tag{1.54}$$

Here, Q_i and τ_i are the number of successfully decoded information nats and the number of channel uses in the i-th time slot, respectively. In general, Q_i, τ_i are random values which follow the random variables $Q(g)$ and $\tau(g)$ with g representing the channel condition. Moreover, (a) follows from the fact that the limits, e.g., $\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} Q_i$, $\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} \tau_i$, exist [12, 13, 14, 17, 68] and (b) is based on the law of large numbers.

- Average transmission power: Following, e.g., [12, 13, 14, 17, 68, 125] and the same discussions as in Section 1.5, the average transmission power is defined as

$$\hat{T} = \frac{\text{Total consumed energy}}{\text{Total time for sending the codewords}} = \lim_{I\to\infty} \frac{\sum_{i=1}^{I} \xi_i}{\sum_{i=1}^{I} \tau_i} = \lim_{I\to\infty} \frac{\frac{1}{I}\sum_{i=1}^{I} \xi_i}{\frac{1}{I}\sum_{i=1}^{I} \tau_i}$$
$$\overset{(a)}{=} \frac{\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} \xi_i}{\lim_{I\to\infty} \frac{1}{I}\sum_{i=1}^{I} \tau_i} \overset{(b)}{=} \frac{E\{\xi(g)\}}{E\{\tau(g)\}}, \tag{1.55}$$

  where ξ_i denotes the consumed energy in the i-th slot, which follows the random variable $\xi(g)$. Also, (a) and (b) follow the same arguments as in (1.54).

- Average rate: The average rate, or the expected rate, is defined as

$$\hat{R} = \lim_{I\to\infty} \frac{1}{I} \sum_{i=1}^{I} R_i = E\{R(g)\} \tag{1.56}$$

  where R_i represents the correctly-decoded data rate at the i-th time slot, e.g., [13, 22]. As seen in Section 1.6.2, depending on the data transmission model, there are cases where the average rate coincides with the long-term throughput. Moreover, as discussed in, e.g., [70, 71], the average rate is more capable to track the short time system performance while the long-term throughput is useful when considering the steady-state behavior of several packet transmissions as time goes to infinity.

- Feedback load: Feedback load is defined as the expected number of feedback bits transmitted in the feedback channel. For the quantized CSI schemes with N quantization regions, the feedback load is obtained as

$$\hat{B}^{\text{QCSI}} = \sum_{n=1}^{N} p_n b_n, \tag{1.57}$$

where b_n is the length of the codeword for encoding the n-th quantization region symbol in (1.2). For the ARQ schemes with a maximum of $M+1$ (re)transmission rounds, the feedback load is obtained by

$$\hat{B}^{\mathrm{ARQ}} = \sum_{m=1}^{M} m \Pr(S_m) + M \Pr(\bar{S}_1, \ldots, \bar{S}_M) \tag{1.58}$$

(for more details, please see paper A).

- Expected number of retransmissions: This is a metric for evaluating the performance of ARQ protocols which is defined as

$$\hat{D}^{\mathrm{ARQ}} = \sum_{m=1}^{M} m \Pr(S_m) + (M+1) \Pr(\bar{S}_1, \ldots, \bar{S}_M). \tag{1.59}$$

  Note that $\hat{D}^{\mathrm{ARQ}} = \hat{B}^{\mathrm{ARQ}} + \Pr(\bar{S}_1, \ldots, \bar{S}_M)$. That is, the only difference between the expected number of retransmission rounds and the feedback load of the ARQ schemes is in the last (re)transmission round where, while the data is retransmitted, no feedback is sent to the transmitter. Moreover, with fixed-length coding, the expected number of (re)transmission rounds is the expected number of channel uses or the expected delay for a packet transmission scaled by a constant.

- Coverage region: The coverage region is an interesting metric particularly for the relay networks which demonstrates the range of distances in which a certain system performance is guaranteed. More detailed definition of the coverage region is presented in paper G which is appended to the thesis.

- Expected information-per-energy: As demonstrated in, e.g., [136], the expected information-per-energy is defined as

$$\hat{e} = \frac{E\{Q(g)\}}{E\{\xi(g)\}} \tag{1.60}$$

  with $E\{Q(g)\}$ and $E\{\xi(g)\}$ given in (1.54) and (1.55), respectively. That is, (1.60) represents the expected number of nats which is successfully received per energy unit.

- Service outage: The service outage is defined as the probability of the event that the instantaneous received data rate is less than a given threshold [137, 138, 139]. In this case, the codeword may be decodable by the receiver while the data rate is less than the desired value.

There are many papers dealing with the fairness particularly in multi-user networks, e.g., [140, 141, 142, 143]. In these works, the goal is to provide some kind of *equality* between the users. In many of the fairness-based approaches weighted metrics are considered where, for instance, the objective is to maximize the weighted sum rate with weights coming from the fairness criteria.

Following the outstanding work by Zheng and Tse [144], there are many papers considering the diversity-multiplexing-tradeoff (DMT) or diversity-multiplexing-delay-tradeoff (DMDT) as the performance yardsticks, e.g., [69, 83, 88, 145, 146]. These metrics establish the necessary tradeoff between reliability and throughput in outage-limited fading channels. However, as DMDT and DMT are metrics for the high SNR regimes and the thesis concentrates on the finite SNR conditions, we do not study these metrics in detail.

Throughout the thesis, we mainly focus on the long-term throughput and the outage probability as the performance yardsticks and the results are obtained under power-limited conditions. Meanwhile papers A, F (resp. paper G), which are appended in the thesis, present some discussions about the feedback load and the expected delay (resp. the coverage region). Also, papers A and C study the system performance in the cases where, along with the transmission power constraints, the outage probability and the other users' received interference power are constrained to be less than given thresholds, respectively.

1.6.2 Data communication models

We consider two, namely, continuous and bursty data communication models [13, 14, 85, 97, 119], which are illustrated in Fig. 1.6. Under the continuous communication model, it is assumed that there is an unlimited amount of information available at the transmitter, which is always active. Under the bursty communication model, on the other hand, it is assumed that there is a long idle period between the packet transmissions. To be more clear, all the available channel uses are utilized in the continuous communication model. This is because data is continuously transmitted, regardless of whether it is decoded or not. In the bursty communication model, on the other hand, the number of ARQ-based channel uses is a random variable which depends on the channel condition. Continuous communication is an appropriate model for the cases where there is a large pool of information nats to be sent to the receivers. On the other hand, the bursty model is better for the cases where the spectrum is used sporadically [14, 85, 119, 147].

The data transmission model affects the performance of the ARQ-based schemes as demonstrated in [13, 14, 66, 85, 97, 119] and in the following.

In general, the long-term throughput and the average transmission power are defined as in (1.54) and (1.55), respectively. Assuming continuous communication and a quasi-static channel, the long-term throughput can be calculated as follows. Let $R(g)$ be the instantaneous data rate of the ARQ approach for a given gain realization g. The total number of information nats that can be decoded in each state is obtained by $Q(g) = L_{\mathrm{c}}R(g)$. Consequently, the long-term throughput is simplified to

$$\hat{\eta} = \frac{E\{L_{\mathrm{c}}R(g)\}}{L_{\mathrm{c}}} = E\{R(g)\} = \hat{R}, \tag{1.61}$$

where $\hat{R}$ is the channel average rate [14, 16, 51, 97].

We denote by $T(g)$ the transmission power random variable of an ARQ scheme for a channel gain realization g. Then, the average transmission power for the continuous

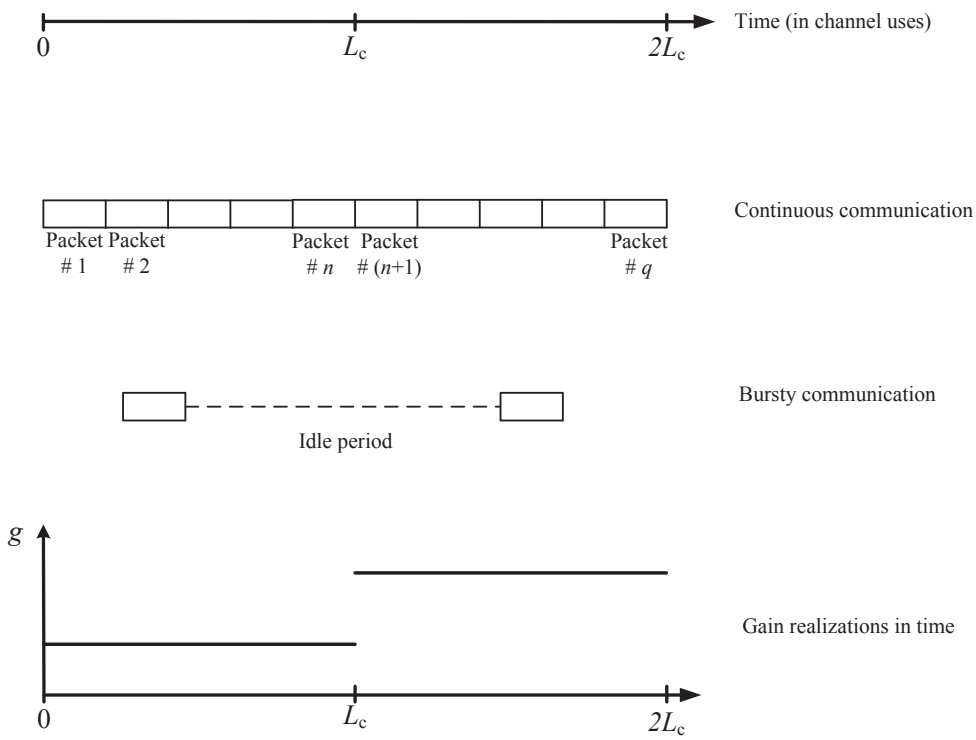


Figure 1.6: An illustration of different data communication models considered throughout the thesis.

communication model is obtained by

$$\hat{T} = \frac{E\{L_c T(g)\}}{L_c} = E\{T(g)\} = \hat{\Phi}, \tag{1.62}$$

as used in, e.g., (1.6).

In the bursty communication model, on the other hand, the elements of the denominator in, e.g., (1.54) and (1.55) are not constant. Hence, the long-term throughput and the average transmission power should be directly calculated based on (1.54) and (1.55), respectively, as in Section 1.5.

One of the differences between the bursty and continuous models returns back to the way the fading channel is observed at the transmission endpoints. As demonstrated in [12, 13, 14, 34, 66, 85, 119], for a large range of fading models, the empirical channel pdf does not match the true channel distribution, if the ARQ packets are sent in a bursty fashion. The reason is that if the channel is *good*, the packet transmission ends at the first transmission round. However, many channel uses are utilized for sending a packet when the channel is *bad*. Hence, a large portion of the data transmission is carried out when the channel experiences low quality, while the transmitter is mostly off when the channel is good. Thus, on average, the channel is seen as *worse* than what it is in reality[7].

With a continuous communication model, on the other hand, the channel gains are observed proportional to their realization probabilities, because the transmitter is always

[7]As discussed in paper F, with a temporally-independent slow-fading model the empirical channel pdf matches the true one even if the data is transmitted in a bursty fashion.

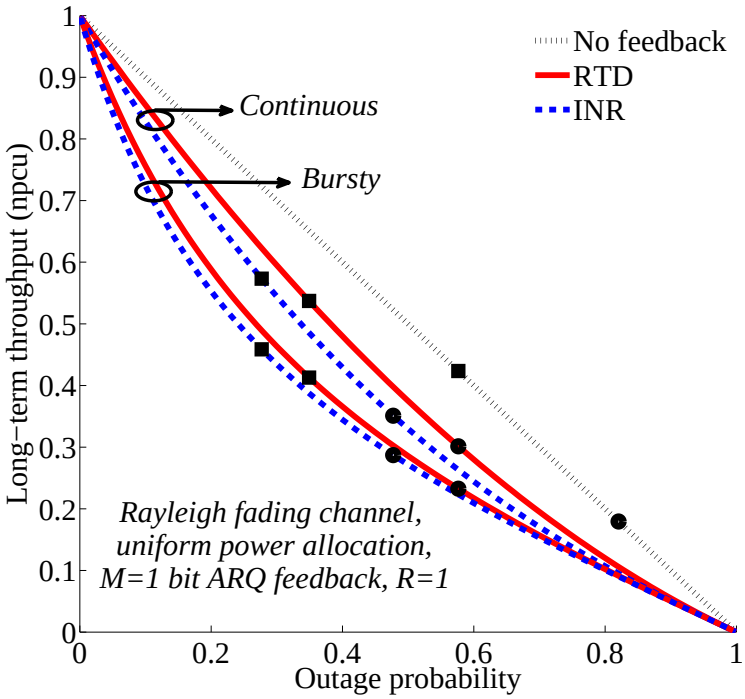


Figure 1.7: Throughput vs outage probability. Uniform power allocation, Rayleigh fading channel, $\mu = 1$, $M = 1$ bit ARQ feedback, fixed-length coding $R = 1$ npcu. Circles (squares) represent the results with transmission power 0dB (3dB).

transmitting. Hence, the empirical channel pdf matches the true one, if the data is transmitted continuously. In other words, a *better* empirical channel pdf is observed in the continuous communication model, compared to the bursty model (please see [12, 13, 14, 34, 66, 85, 119] for more detailed discussions).

Considering Rayleigh fading quasi-static channels, Fig. 1.7 demonstrates the long-term throughput versus the outage probability for different ARQ protocols and data communication models. With the same transmission power, better system performance is achieved by the INR protocol, compared to the RTD. As expected, the ARQ protocols lead to better outage probability and long-term throughput, compared to the open-loop communication setup. Also, higher throughput is achievable in the continuous model, in comparison with the bursty data communication model.

Finally, note that the performance of the quantized CSI-based approaches is not affected by the communication models. The reason is that each packet of the quantized CSI schemes is of fixed length L, independent of the channel condition. That is, considering (1.54) and (1.55), we have $\tau_i = L$, $\forall i$, which is deterministic. Thus, we have $\sum_{i=1}^{I} \tau_i = IL$ which leads to

$$\hat{\eta} = \lim_{I\to\infty} \frac{\sum_{i=1}^{I} Q_i}{\sum_{i=1}^{I} \tau_i} = \lim_{I\to\infty} \frac{\sum_{i=1}^{I} Q_i}{IL} = \lim_{I\to\infty} \frac{1}{I} \sum_{i=1}^{I} \frac{Q_i}{L} = \lim_{I\to\infty} \frac{1}{I} \sum_{i=1}^{I} R_i = E\{R(g)\} = \hat{R}. \tag{1.63}$$

Therefore, independent of the communication model, the long-term throughput degener-

ates to the average rate in the quantized CSI schemes (the same procedure can be applied for the average power).

To further clarify the differences between the bursty and continuous models, we close the section with the following example.

Example 1: Shen, et. al, have previously shown that:

- With $M \to \infty$ retransmissions and a quasi-static fading model, the throughput of the variable-length coding INR protocol converges to the channel ergodic capacity $C = \int_0^\infty f_G(\upsilon) \log(1+\upsilon) \mathrm{d}\upsilon$ if the data is transmitted continuously [14, lemma 2].
- Using uniform power allocation, continuous communication and a quasi-static fading model, the same throughput is obtained by the INR ARQ using a maximum of $M+1$ (re)transmissions and the quantized CSI-based approach with N quantization regions, if $M+1 = N$ [14, lemma 3].

However, using paper F and because of the worse empirical distribution, it can be easily proved that there is no ARQ scheme that can reach the channel ergodic capacity, if the data is transmitted in a bursty fashion and the channel is quasi-static. Also, the throughput achieved by INR ARQ protocol using a maximum of $M+1$ (re)transmissions is less than the throughput achieved by the quantized CSI approach having $N = M+1$ quantization regions, if the data is sent in a bursty fashion and the channel is quasi-static. These points, which are because the good channels are not fully utilized by the ARQ in the bursty model, are further elaborated in paper F presented in Chapter 2.

1.7 Summary of our works

During the last five years, we have been working on different aspects of the partial CSI-based networks. The results have been obtained in a wide range of network configurations/fading models and for various performance metrics/constraints. As a result, it is difficult to categorize them into non-overlapping groups. In the following, we attempt to categorize the developed works from two perspectives. First, we group our works based on the partial CSI model. Second, we categorize our papers from the network configuration point of view.

1.7.1 Grouping our works based on the partial CSI model

From the partial CSI model point of view, the developed approaches can be divided into four categories. These categories, which are demonstrated in Fig. 1.8, are as follows.

- CSI quantization: In [30, 49, 50, 60, 98, 99, 100, 101, 102, 103], we have studied the performance of the communication setups in the presence of the quantized CSI. In these works, we have followed the same approach as described in Section 1.4; a quantization function is applied at the receiver and the transmitter is provided with quantized CSI that is used for optimal rate/power allocation. Also, [60, 99] present discussions on optimal feedback bit distribution in OFDM and MIMO broadcast

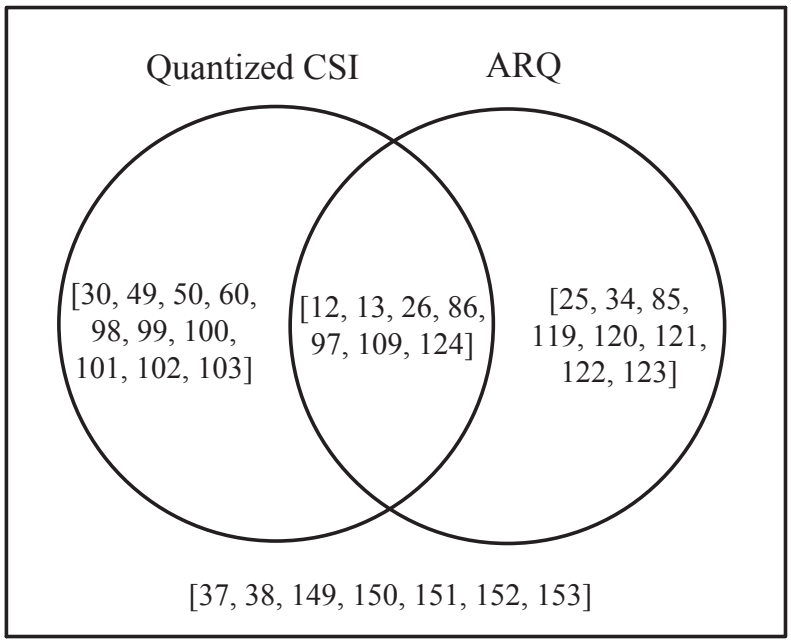


Figure 1.8: Grouping our works based on the limited feedback model.

channels, respectively. In all papers, except [99] which is based on random vector quantization, we have studied the optimal quantization boundaries and their effect on the system performance. Moreover, in all of these works the goal is to maximize the long-term (sum) throughput which is optimized in power-limited (resp. outage-limited) condition [30, 60, 98, 99, 100, 101, 102, 103] (resp. [49, 50]). Meanwhile, [98] presents different fairness schemes for the multi-user networks and [30] studies the feedback load of the quantized CSI-based techniques using dynamic quantizers. In [30, 50, 60, 98, 99, 100, 101, 102, 103], the feedback signal is supposed to be received by the transmitter error-free. The system performance in the presence of erroneous feedback signals is investigated in [49]. Finally, it is worth noting that, as there is no closed-form solution for the optimal quantization boundaries maximizing the throughput, [30, 49, 50, 60, 98, 99, 100, 101, 102] present discussions/algorithms for the numerical solution of the optimal quantizers via implementation of iterative optimization algorithms. Also, [98, 99, 103] demonstrate analytical approximations for the power-limited throughput of the quantized CSI-based approaches.

- ARQ feedback: Considering different communication setups, we have investigated the performance of the ARQ-based protocols in [25, 34, 85, 119, 120, 121, 122, 123]. Here, the results are obtained for the INR, the RTD and the basic ARQ protocols. Also, [122] demonstrates the superiority of the hybrid ARQ protocols over the repetition coding-based techniques and [119] analyzes the performance of STC-based MIMO-ARQ protocols. In [25, 34, 119, 120, 121], it is attempted to develop a fairly general framework for studying the data transmission efficiency of the ARQ protocols. The system performance is evaluated for different quasi-static, slow- and fast-fading models which, as shown in [25, 34, 119], can be mapped to each other. More-

over, [34, 85, 119, 121, 122] present different comparisons between data transmission efficiency of the ARQ protocols in the bursty and continuous data communication models. The results have been obtained under power-limited condition and the objective functions are the long-term throughput or the outage probability. Meanwhile, [119, 121, 122] (resp. [120]) study the feedback load/expected delay (resp. coverage region) of the ARQ-based systems as well. The optimization parameters are considered to be the (re)transmission powers/rates and we investigate the effect of variable-length coding on the system performance, e.g., [34, 85, 119, 120, 121]. In these works, the feedback bits are assumed to be received error-free, while [121, 148] investigate the performance of the ARQ protocols in the presence of an unreliable feedback channel. Finally, as some of the probability terms of the ARQ protocols can not be expressed with a closed-form solution, different approximation/bounding techniques are presented for the ARQ protocols in [119, 120, 122, 123].

- Combination/comparison of the quantized CSI and ARQ schemes: In [12, 13, 26, 86, 97, 109, 124], we demonstrate different comparisons or combinations of the quantized CSI and the ARQ protocols[8]. In all papers, the feedback signal is supposed to be received delay-free, while [26] evaluates the system throughput in the presence of delayed quantized CSI feedback. In [12, 86], the CSI quantization is modeled by an additive Gaussian noise, while the quantization model of [13, 26, 97, 109, 124] is the same as the one presented in Section 1.4. In order to combine the ARQ and the quantized CSI schemes, the quantized CSI provides some rough pre-knowledge for the transmitter(s) and then the ARQ protocols are implemented to compensate the transmitter(s) imperfect knowledge about the channel quality. As demonstrated in [13, 97, 109, 124], depending on the fading model, there are cases where the ARQ, the quantized CSI or their combinations can be mapped to each other, in the sense that the same system performance, e.g., throughput, is achieved by these schemes. Furthermore, [13, 26] present comparisons between the performance of the quantized CSI and the ARQ protocols in different fading models. The comparisons are in terms of the power-limited throughput, the outage probability, the feedback load and the robustness to the erroneous feedback signal which demonstrate the equivalency or the superiority of these approaches in different circumstances.

- Others: The performance of the communication setups in the presence of full CSI has been studied in [149, 150, 151, 152]. Our reason for considering the full CSI assumption is to simplify the analytical analysis and investigate the optimal rate/power allocation problems in more details. In all these works, except [152] which deals with coordinated multi-point (CoMP) networks, we have considered spectrum sharing, also called cognitive radio, channels. Particularly, [149, 150, 151] analyze the effect of sequential decoders, spatial correlation and the users' security requirement on the performance of the spectrum sharing networks, respectively. Finally, [153] and [37, 38] investigate the data transmission efficiency of the spectrum sharing networks in the cases with no CSI and in the presence of one bit interference-avoiding

[8]The main focus of [12, 86, 109, 124] is on the quantized CSI approach.

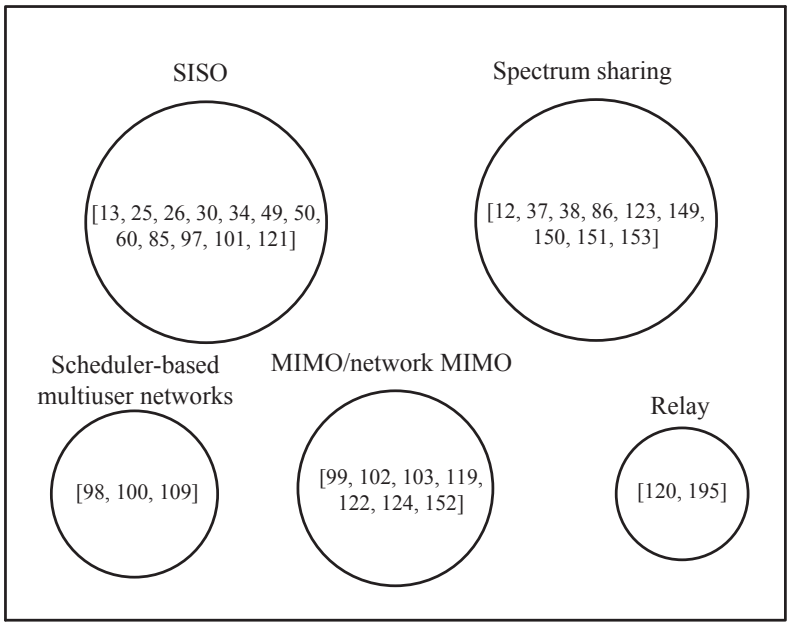


Figure 1.9: Grouping our works based on the network configuration.

signal, respectively. The interference-avoiding feedback is a signal to indicate the presence of the other users, based on which the users activeness is scheduled. As demonstrated in all papers, considerable performance improvement is achieved with feedback rates as low as 1 bps.

1.7.2 Grouping our works based on the network configuration

The partial CSI feedback is a challenging problem for (almost) all kinds of communication setups. Therefore, it has been considered by the researchers for many network configurations, ranging from the single-user single-antenna setups to the large-scale multi-user network MIMO. In our works, the limited-feedback problem has been studied for the following network configurations (please see Fig. 1.9 as well):

- Single-user single-antenna networks: In [13, 25, 26, 30, 34, 49, 50, 60, 85, 97, 101, 121], we consider the single-user single-antenna networks. This is the simplest network configuration in which a single-antenna transmitter sends the data to its corresponding receiver. Therefore, the network configuration allows us to study the effect of partial CSI as well as the optimal quantization boundaries and the transmission rates/powers in detail, without requiring many approximations, upper/lower bounds or simplifying assumptions. Moreover, the results provide the basis for studying the other network configurations such as the MIMO/network MIMO, the relay and the spectrum sharing networks.

  In [30, 49, 50, 60, 101] and [25, 34, 85, 121] the quantized CSI and the ARQ protocols are considered, respectively, while [13, 26] consider the combination/comparisons of the two schemes. Here, the network performance is studied from different aspects;

the effect of noisy and delayed feedback signals is evaluated in [13, 49, 121] and [26, 30], respectively. Moreover, [26, 30] exploit the channel temporal correlation to increase the system throughput via implementation of feedback subsampling and dynamic quantizers, respectively. In [34], we develop new reinforcement algorithms for adaptive power allocation in temporally-correlated fading channels. The power-limited throughput of the fast-fading channels utilizing ARQ and quantized CSI feedback is studied in [25, 26], respectively. Also, [13] presents comparisons between the ARQ and the quantized CSI schemes and demonstrates the equivalency or the superiority of these schemes in different conditions. Furthermore, [97] combines the quantized CSI and the ARQ protocols and shows the equivalency of these schemes in quasi-static channels. Considering different fading models, [34, 49, 85, 121] obtain the optimal power allocation of the ARQ schemes in terms of throughput and outage probability. Also, the outage probability of the quantized CSI- and the ARQ-based single-user networks is investigated in [34, 49, 50]. The results indicate that, with limited feedback, optimal power allocation leads to substantial outage probability reduction [34, 49, 121]. However, the effect of optimal power allocation on the throughput is not significant at high SNRs [34, 49, 50, 85, 121].

- Spectrum sharing networks: Spectrum is a scarce valuable resource in today's wireless communication networks; with ever-increasing number of wireless devices communicating at high data rates, there is growing demand for spectrum resources. This point has led to complaints about spectrum shortage which is expected to grow even more in the coming years.

  To tackle the spectrum shortage problem, several dynamic spectrum management solutions have been proposed among which spectrum sharing is one of the most promising ones, e.g., [154, 155, 156, 157, 158]. In a spectrum sharing network, unlicensed secondary users (SUs) are permitted to work within the spectrum resources of licensed primary users (PUs) as long as the PUs quality-of-service (QoS) requirements are satisfied. In general, there are two methods for spectrum sharing. In a method widely referred to as the interference-avoiding paradigm [154, 155, 156], the SUs are not permitted to work within the PUs activation period. In another scheme, normally denoted simultaneous or controlled transmission [157, 158, 159, 160, 161, 162, 163], a SU can simultaneously coexist with a PU as long as it works under a certain interference level imposed by the PU QoS requirements.

  In our works, we concentrate on the simultaneous transmission paradigm of the spectrum sharing networks [12, 37, 38, 86, 123, 149, 150, 151, 153]. Here, the goal is to maximize the SU achievable rates with different outage probability [123, 150], received interference power [12, 37, 38, 86, 149, 150, 151, 153] or received signal-to-interference-and-noise ratio (SINR) [37, 38, 151, 153] constraints for the PU. The results are obtained in the presence of full CSI [149, 150, 151], no CSI [153], interference-avoiding signal [37, 38], ARQ feedback [123] or the combination of the ARQ and quantized CSI feedback [12, 86]. In [123, 150], we investigate the effect of spatial correlation between the fading coefficients on the network achievable rates.

Also, [149] develops an interference-free spectrum sharing scheme via implementation of sequential decoders. In [12, 86] (resp. [123]), the ARQ feedback is considered for the SU (resp. for the PU) and adaptive power allocation is utilized to maximize the interference-limited (resp. outage-limited) throughput. The security of the spectrum sharing users is addressed in [151] where the SU security is guaranteed via rate allocation. Finally, [37, 38, 123, 149, 153] show that, depending on the PU QoS requirements, there are cases where the maximum throughput is achieved by combination of the simultaneous transmission and the interference-avoiding spectrum sharing paradigms. That is, to maximize the SU throughput, the SU should work in a time division multiple access (TDMA) fashion, determined by the PU QoS requirement.

- Scheduler-based multi-user networks: It has been demonstrated both practically and theoretically [39, 52, 61, 65, 141, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174] that employment of adaptive modulation and scheduling leads to substantial performance improvement in multi-user systems, normally called *multi-user diversity*. Traditionally, the fading is considered as an unreliability source which should be mitigated. In the multi-user diversity context, however, the channel fading has a positive impact and is helpful for improving the system performance [39, 52, 61, 65, 141, 164, 165, 166, 167, 168, 169]. This is because in a system with a number of users experiencing independent fading conditions it is more likely that, at each time instant, one of the users experiences *good* channel quality. Hence, the data transmission efficiency is improved by always communicating the *best* users.

  In order to prioritize among the users and select the proper modulation for the best user, the scheduler must in theory know the channels perfectly which, due to feedback signaling overhead, is not practically feasible. Hence, a quantized representation of the CSI, expressed via a limited number of feedback bits, is normally provided at the transmitters.

  In [98, 100, 109], we analyze the performance of the multi-user networks in the presence of partial CSI feedback. Here, it is mainly focused on the CSI quantization, while [109] presents some discussions about the ARQ protocols as well. The proposed schemes are based on the implementation of the schedulers which exploit the received CSI for selecting the best user maximizing the network sum throughput. Moreover, [100] develops simple fairness schemes and investigates the system performance in the cases with different users activeness probabilities. The effect of spatial correlation on the performance of the scheduler-based multi-user networks is studied in [98]. Finally, [109] proposes a two-step CSI feedback approach, where the users scheduling is performed based on some rough initial CSI feedback from all users and then the transmitter receives more accurate information about the channel quality of the scheduled user. As demonstrated in [100, 109], optimal channel quantization and the implementation of the proposed two-step CSI feedback approach lead to substantial performance improvement for the multi-user networks with very limited feedback load.

- MIMO/network MIMO: MIMO transmission is one of the best approaches for exploiting the spatial diversity, particularly over rich scattered environments. MIMO has revolutionized the modern wireless communications, is a key part of most current standards such as WiFi (IEEE 802.11) and WiMax (IEEE 802.16) [1, 2], and is expected to be the core technology for the next generation broadband wireless communication systems. From another perspective, CoMP, also known as network MIMO, is one of the most promising techniques for improving the data transmission efficiency of wireless cellular networks [175, 176, 177, 178]. The main idea of a CoMP network is to allow geographically separated base stations (BSs) to cooperate in serving the users. The cooperation is achieved through high speed backhaul links such that the users' data and CSI can be shared between the BSs. The performance of the MIMO and network MIMO systems, however, depends strongly on the amount of CSI provided at the transmitter(s). This is the main motivation for studying the MIMO/network MIMO systems under limited CSI conditions, which has become a hot topic during the last decade.

  In [99, 102, 103, 119, 122, 124, 152], we evaluate the data transmission efficiency of the MIMO and network MIMO systems in the presence of partial CSI feedback; the performance of the MIMO-ARQ networks is studied in [119] where we consider different aspects of the network such as the presence of power amplifiers nonlinearity, large-scale MIMO, bursty/continuous communication and temporal/spatial power allocation. The effect of CSI quantization and optimal feedback bit distribution on the performance of the MIMO broadcast systems is studied in [99]. In [103], we obtain the optimal, in terms of throughput, feedback bit distribution rules between the phase and the amplitude of the multiple-input and single-output (MISO) setups. The expected sum throughput of the CoMP networks is investigated in [102, 122, 124, 152]. Here, the results are obtained in the presence of the ARQ [122], the quantized CSI [102, 124] or the full CSI [152]. Finally, [122] presents mappings between the CoMP-ARQ and single-user ARQ systems and [152] determines the optimal power allocation, in terms of the sum throughput, in the cases with different users activeness probabilities.

- Relay networks: Relay-assisted communication is one of the promising techniques that have been proposed for the wireless networks [179, 180, 181, 182, 183, 184, 185, 186, 187]. The main idea of a relay network is to improve the data transmission efficiency by implementation of intermediate relay nodes which support the data transmission from a source to a destination. The relay networks have been adopted in the long-term evolution advanced (LTE-A) standardization [188] and are expected to be one of the core technologies for the next generation cellular systems. The data transmission efficiency of the limited-feedback relay networks have been studied in many papers, e.g., [112, 189, 190, 191, 192, 193, 194].

  In [120, 195], we have investigated the throughput, the outage probability and the coverage region of the relay networks implementing different ARQ protocols. Here, adaptive power allocation is utilized to improve the system performance under dif-

ferent sum and individual power constraints for the source and the relay. In [120], only one of the source or the relay is active in each retransmission round. In [195], on the other hand, the source and the relay use STCs to make a distributed cooperative antenna and retransmit the data simultaneously in rounds when the relay is active. As demonstrated in the papers, adaptive power allocation in the relay-ARQ networks results in substantial coverage region increment and outage probability reduction. Moreover, the papers present analytical upper/lower bounds for the throughput and the outage probability of the relay-INR systems.

1.7.3 A summary of the appended papers

Among the developed works, papers A-G are appended to the thesis. The reason for selecting the considered papers is that they provide an overview of our developed works. In the following, we briefly introduce the appended papers.

Paper A (On Hybrid ARQ and Quantized CSI Feedback Schemes in Quasi-Static Fading Channels): Considering continuous data communication over quasi-static channels, this paper compares the data transmission efficiency of the communication setups using ARQ and quantized CSI. The problem is cast in form of maximizing the throughput subject to transmission power and outage probability constraints. The performance of the ARQ and quantized CSI schemes is compared from different points of view, such as the outage-limited throughput, feedback load, complexity and robustness to erroneous feedback signals, which show the equivalency or the superiority of these approaches in different circumstances.

Paper B (Feedback Subsampling in Temporally-Correlated Slowly-Fading Channels using Quantized CSI): In this paper, we study the problem of feedback subsampling in temporally-correlated wireless networks. Under different power constraints, the system data transmission efficiency is studied in two scenarios. First, we focus on the case where the codewords span one fading block. In the second scenario, the throughput is determined for the case where the codewords are so long that a finite number of correlated gain realizations are experienced during each codeword transmission. The results show the feedback subsampling as an efficient scheme increasing the throughput with limited feedback rates.

Paper C (On the Average Rate of HARQ-Based Quasi-Static Spectrum Sharing Networks): Here, we study the effect of ARQ protocols on the average rate of spectrum sharing networks. With different SU transmission power constraints, the results are obtained under the PU limited received interference condition, when there is (im)perfect CSI about the SU-PU link. Finally, the results are extended to the cases where the PU and the SU data transmissions are constrained to have limited outage probability.

Paper D (On ARQ-Based Fast-Fading Channels): This paper investigates the performance of basic and INR ARQ protocols in fast-fading channels where a number of channel realizations are experienced in each retransmission round. Different metrics are evaluated in power-limited conditions and we present mappings/comparisons between the performance of ARQ protocols in different fading conditions. For instance, compared to slow-fading and quasi-static channels, a fast-fading channel results in a higher throughput

for both basic and INR ARQ.

Paper E (On the Average Rate of Quasi-Static Fading Channels with ARQ and CSI Feedback): The combination of the quantized CSI and ARQ protocols is addressed in this paper; the transmitter is initially provided with quantized CSI, expressed via a limited number of feedback bits, and then the ARQ is implemented to compensate the transmitter imperfect knowledge about the channel quality. Particularly, it is shown that, depending on the fading condition and the data communication model, there are cases where the combination of the ARQ and quantized CSI schemes can be mapped to the case utilizing only one of them.

Paper F (On the Performance of MIMO-ARQ Systems with Channel State Information at the Receiver): Here, we try to develop a fairly general framework for studying the performance of ARQ protocols. We show that, for many performance metrics, the data transmission efficiency of MIMO-ARQ systems can be demonstrated as a function of parameters which are scheme-dependent and not metric-dependent. Then, the results are used to study different aspects of MIMO-ARQ such as the effect of nonlinear power amplifiers, large-scale MIMO-ARQ, adaptive power allocation and different data communication models. The results, which are valid for various forward and feedback channel models, show the efficiency of the MIMO-ARQ techniques in different conditions.

Paper G (On a Relay-ARQ Network using Adaptive Power Allocation): This paper investigates the performance of relay networks in the presence of ARQ feedback and adaptive power allocation. The throughput and the outage probability of the RTD and INR protocols are studied for independent and spatially-correlated fading channels. The results are obtained for the cases where there is a sum power constraint on the source and the relay or when each of the source and the relay are power-limited individually. With adaptive power allocation, the results demonstrate the efficiency of relay-ARQ techniques in different conditions.

1.8 Conclusion

In the introduction to the thesis, we present the basis for the performance analysis of the limited-feedback schemes. We focus on the quantized CSI and the ARQ-based schemes of the limited-feedback systems. Also, we discuss the possible extensions of the partial CSI protocols and summarize the techniques that we have developed during the last five years. More detailed discussions about the proposed partial CSI feedback approaches are presented in the second part of the thesis.

Bibliography

[1] S. Nanda, R. Walton, J. Ketchum, M. Wallace, and S. Howard, "A high-performance MIMO OFDM wireless LAN," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. 101–109, Feb. 2005.

[2] A. Ghosh, D. R. Wolter, J. G. Andrews, and R. Chen, "Broadband wireless access with WiMax/802.16: current performance benchmarks and future potential," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. 129–136, Feb. 2005.

[3] ETSI Normalization Comitee, "Radio broadcast systems, digital audio broadcasting (DAB) to mobile, portable and fixed receiver," Norm ETSI doc. EN300401, European Telecommunications Standards Institute, Sophia-Antipolis, France, 2006.

[4] ETSI Normalization Comitee, "Digital video broadcasting (DVB); framing structure, channel coding and modulation for digital terrestrial television," Norm ETSI doc. EN300401, European Telecommunications Standards Institute, Sophia-Antipolis, France, 2006.

[5] T. T. Kim, "Limited feedback information in wireless communications: Transmission schemes and performance bounds," Ph.D. dissertation, KTH School of Electrical Engineering, 2008.

[6] K. D. Nguyen, "Adaptive transmission for block-fading channels," Ph.D. dissertation, University of South Australia, 2009.

[7] ETSI Normalization Comitee, "Physical layer on the radio path; general description," Norm ETSI doc. 3GPP TS45.001, European Telecommunication Standards Institute, Sophia-Antipolis, France, 2009.

[8] A. Lozano, R. W. Heath, and J. G. Andrews, "Fundamental limits of cooperation," arXiv:1204.0011v1 2012, available at: http://arxiv.org/abs/1204.0011v1.

[9] N. Jindal and A. Lozano, "A unified treatment of optimum pilot overhead in multipath fading channels," *IEEE Trans. Commun.*, vol. 58, no. 10, pp. 2939–2948, Oct. 2010.

[10] A. Lozano and D. Porrat, "Non-peaky signals in wideband fading channels: Achievable bit rates and optimal bandwidth," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 246–257, Jan. 2012.

[11] E. Biglieri, J. Proakis, and S. Shamai, "Fading channels: information-theoretic and communications aspects," *IEEE Trans. Inf. Theory*, vol. 44, no. 6, pp. 2619–2692, Oct. 1998.

[12] B. Makki and T. Eriksson, "On the average rate of HARQ-based quasi-static spectrum sharing networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 65–77, Jan. 2012.

[13] ——, "On hybrid ARQ and quantized CSI feedback schemes in quasi-static fading channels," *IEEE Trans. Commun.*, vol. 60, no. 4, pp. 986 –997, April 2012.

[14] C. Shen, T. Liu, and M. P. Fitz, "On the average rate performance of hybrid-ARQ in quasi-static fading channels," *IEEE Trans. Commun.*, vol. 57, no. 11, pp. 3339–3352, Nov. 2009.

[15] M. K. Chang, C. S. Lim, and C. C. J. Kuo, "Power control for packet-based wireless communication systems," in *WCNC*, vol. 1, March 2003, pp. 542–546.

[16] C. Shen and M. P. Fitz, "Hybrid ARQ in multiple-antenna slow fading channels: Performance limits and optimal linear dispersion code design," *IEEE Trans. Inf. Theory*, vol. 57, no. 9, pp. 5863–5883, Sept. 2011.

[17] D. Tuninetti, "On the benefits of partial channel state information for repetition protocols in block fading channels," *IEEE Trans. Inf. Theory*, vol. 57, no. 8, pp. 5036–5053, Aug. 2011.

[18] J. S. Harsini, F. Lahouti, M. Levorato, and M. Zorzi, "Analysis of non-cooperative and cooperative type II hybrid ARQ protocols with AMC over correlated fading channels," *IEEE Trans. Wireless Commun.*, vol. 10, pp. 877–889, March 2011.

[19] H. Seo and B. G. Lee, "Optimal transmission power for single- and multi-hop links in wireless packet networks with ARQ capability," *IEEE Trans. Commun.*, vol. 55, no. 5, pp. 996–1006, May 2007.

[20] A. K. Karmokar, D. V. Djonin, and V. K. Bhargava, "Delay constrained rate and power adaptation over correlated fading channels," in *GLOBECOM*, vol. 6, Nov. 2004, pp. 3448–3453.

[21] D. V. Djonin, A. K. Karmokar, and V. K. Bhargava, "Joint rate and power adaptation for type-I hybrid ARQ systems over correlated fading channels under different buffer-cost constraints," *IEEE Trans. Veh. Technol.*, vol. 57, no. 1, pp. 421–435, Jan. 2008.

[22] T. T. Kim and M. Skoglund, "On the expected rate of slowly fading channels with quantized side information," *IEEE Trans. Commun.*, vol. 55, no. 4, pp. 820–829, April 2007.

[23] P. Pagani and P. Pajusco, "Characterization and modeling of temporal variations on an ultrawideband radio link," *IEEE Trans. Antennas Propag.*, vol. 54, no. 11, pp. 3198–3206, Nov. 2006.

[24] J. Tsao, D. Porrat, and D. Tse, "Prediction and modeling for the time-evolving ultra-wideband channel," *IEEE J. Sel. Topics Signal Process.*, vol. 1, no. 3, pp. 340–356, Oct. 2007.

[25] B. Makki, A. Graell I Amat, and T. Eriksson, "On ARQ-based fast-fading channels," *IEEE Commun. Lett.*, vol. 16, no. 12, pp. 1921–1924, Dec. 2012.

[26] B. Makki and T. Eriksson, "Feedback subsampling in temporally-correlated slowly-fading channels using quantized CSI," *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2282–2294, June 2013.

[27] T. Eriksson and T. Ottosson, "Compression of feedback in adaptive OFDM-based systems using scheduling," *IEEE Commun. Lett.*, vol. 11, no. 11, pp. 859–861, Nov. 2007.

[28] K. Huang, R. W. Heath, and J. G. Andrews, "Limited feedback beamforming over temporally-correlated channels," *IEEE Trans. Signal Process.*, vol. 57, no. 5, pp. 1959–1975, May 2009.

[29] S. Akoum and R. W. Heath, "Limited feedback for temporally correlated MIMO channels with other cell interference," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5219–5232, Oct. 2010.

[30] B. Makki and T. Eriksson, "CSI feedback in correlated slow-fading channels," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1294–1297, Dec. 2011.

[31] T. Kim, D. J. Love, B. Clerckx, and S. Kim, "Differential rotation feedback MIMO system for temporally correlated channels," in *GLOBECOM*, 2008, pp. 1–5.

[32] T. Kim, D. J. Love, and B. Clerckx, "MIMO systems with limited rate differential feedback in slowly varying channels," *IEEE Trans. Commun.*, vol. 59, no. 4, pp. 1175–1189, April 2011.

[33] R1-062772, "Compressed CQI reporting scheme," NEC, RAN WG1 meeting 46, Seoul, Republic of Korea, Oct. 2006.

[34] B. Makki, A. Graell I Amat, and T. Eriksson, "Green communication via power-optimized HARQ protocols," *IEEE Trans. Veh. Technol.*, 2013, accepted, in press.

[35] S. Ekbatani, "Communication over multiple antenna fading channels using quantized and erroneous feedback information," Ph.D. dissertation, University of California, Irvine, 2008.

[36] R. A. Tannious and A. Nosratinia, "Cognitive radio protocols based on exploiting hybrid ARQ retransmissions," *IEEE Trans. Wireless Commun.*, vol. 9, no. 9, pp. 2833–2841, Sept. 2010.

[37] B. Makki and T. Eriksson, "On the ergodic achievable rates of spectrum sharing networks with finite backlogged primary users and an interference indicator signal," *IEEE Trans. Wireless Commun.*, vol. 11, no. 9, pp. 3079–3089, Sept. 2012.

[38] ——, "Interference management using one bit feedback," in *European Wireless*, 2011, pp. 1–5.

[39] T. Eriksson and T. Ottosson, "Compression of feedback for adaptive transmission and scheduling," *Proc. of the IEEE*, vol. 95, no. 12, pp. 2314–2321, Dec. 2007.

[40] G. Caire, N. Jindal, and M. Kobayashi, "Achievable rates of MIMO downlink beamforming with non-perfect CSI: a comparison between quantized and analog feedback," in *Asilomar*, 2006, pp. 354–358.

[41] S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Transmission over slowly fading channels using unreliable quantized feedback," in *DCC*, March 2007, pp. 353–362.

[42] 3GPP TS 36.211 v9.1.0, "Evolved universal terrestrial radio access (E-UTRA); physical channels and modulation," March 2010.

[43] J. Jin, Q. Wang, C. Lin, H. Yang, and Y. Wang, "Coordinated multi-point transmission with limited feedback," in *GLOBECOM*, Dec. 2010, pp. 850–854.

[44] D. Kim, O. S. Shin, and K. B. Lee, "Efficient limited feedback schemes for network MIMO systems," in *GLOBECOM*, Dec. 2011, pp. 1–6.

[45] F. Yuan and C. Yang, "Bit allocation between per-cell codebook and phase ambiguity quantization for limited feedback coordinated multi-point transmission systems," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2546–2559, Sept. 2012.

[46] D. Kim, O. S. Shin, I. Sohn, and K. B. Lee, "Channel feedback optimization for network MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 3315–3321, Sept. 2012.

[47] J. Li, A. Papadogiannis, R. Apelfrojd, T. Svensson, and M. Sternad, "Performance evaluation of coordinated multi-point transmission schemes with predicted CSI," in *PIMRC*, Sept. 2012, pp. 1055–1060.

[48] T. R. Lakshmana and T. Papadogiannis, A. ; Jingya Li ; Svensson, "On the potential of broadcast CSI for opportunistic coordinated multi-point transmission," in *PIMRC*, Sept. 2012, pp. 1262–1267.

[49] B. Makki and T. Eriksson, "Data transmission in the presence of noisy channel state feedback and outage probability constraint," in *ISITA*, 2010, pp. 458–463.

[50] ——, "Data transmission in the presence of channel state feedback and outage probability constraint," in *VTC*, 2010, pp. 1–5.

[51] S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Throughput maximization over slowly fading channels using quantized and erroneous feedback," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2528–2533, Sept. 2009.

[52] S. Sanayei and A. Nosratinia, "Exploiting multiuser diversity with only 1-bit feedback," in *WCNC*, vol. 2, March 2005, pp. 978–983.

[53] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inf. Theory*, vol. 43, no. 6, pp. 1986–1992, Nov. 1997.

[54] D. Gesbert and M.-S. Alouini, "How much feedback is multi-user diversity really worth?" *ICC*, vol. 1, pp. 234–238, June 2004.

[55] J. C. Roh and B. D. Rao, "Transmit beamforming in multiple-antenna systems with finite rate feedback: a VQ-based approach," *IEEE Trans. Inf. Theory*, vol. 52, no. 3, pp. 1101–1112, March 2006.

[56] Y. He and S. Dey, "Power allocation in spectrum sharing cognitive radio networks with quantized channel information," *IEEE Trans. Commun.*, vol. 59, no. 6, pp. 1644–1656, June 2011.

[57] S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Outage behavior of slow fading channels with power control using partial and erroneous CSIT," *IEEE Trans. Inf. Theory*, vol. 56, no. 12, pp. 6097–6102, Dec. 2010.

[58] N. Jindal, "MIMO broadcast channels with finite-rate feedback," *IEEE Trans. Inf. Theory*, vol. 52, no. 11, pp. 5045–5060, Nov. 2006.

[59] Z. Rezki and M.-S. Alouini, "On the capacity of cognitive radio under limited channel state information over fading channels," in *ICC*, 2011, pp. 1–5.

[60] B. Makki and T. Eriksson, "Efficient channel quality feedback signaling using transform coding and bit allocation," in *VTC*, May 2010, 1-5.

[61] D. J. Love, R. W. Heath, V. K. N. Lau, D. Gesbert, and M. Rao, B. D. ; Andrews, "An overview of limited feedback in wireless communication systems," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 8, pp. 1341–1365, Oct. 2008.

[62] R1-070368, "System level comparison of best-M and DCT-based CQI compression schemes," Huawei, RAN1 meeting 47bis, Sorrento, Italy, Jan. 2007, available at *www.3gpp.org*.

[63] R1-060018, "Performance evaluation of EUTRA downlink CQI feedback schemes," Motorola, RAN1 meeting 44, Helsinki, Finland, Jan. 2006.

[64] R1-062575, "Further analysis on DCT based CQI reporting scheme," LG Electronics, RAN1 meeting 46, Seoul, Republic of Korea, Oct. 2006.

[65] A. Haghighat, Z. Lin, and G. Zhang, "Haar compression for efficient CQI feedback signaling in 3GPP LTE systems," April 2008, pp. 819–823.

[66] P. Wu and N. Jindal, "Performance of hybrid-ARQ in block-fading channels: A fixed outage probability analysis," *IEEE Trans. Commun.*, vol. 58, no. 4, pp. 1129–1141, April 2010.

[67] S. Y. Park and D. J. Love, "Hybrid ARQ protocol for multi-antenna multicasting using a common feedback channel," *IEEE Trans. Commun.*, vol. 59, no. 6, pp. 1530–1542, June 2011.

[68] G. Caire and D. Tuninetti, "The throughput of hybrid-ARQ protocols for the Gaussian collision channel," *IEEE Trans. Inf. Theory*, vol. 47, no. 5, pp. 1971–1988, July 2001.

[69] H. El Gamal, G. Caire, and M. O. Damen, "The MIMO ARQ channel: Diversity-multiplexing-delay tradeoff," *IEEE Trans. Inf. Theory*, vol. 52, no. 8, pp. 3601–3621, Aug. 2006.

[70] R. Narasimhan, "Throughput-delay performance of half-duplex hybrid-ARQ relay channels," in *ICC*, May 2008, pp. 986–990.

[71] ——, "Delay-limited throughput of cooperative multiple access channels with hybrid-ARQ," in *ISIT*, July 2008, pp. 409–413.

[72] N. Arulselvan and R. Berry, "Efficient power allocations in wireless ARQ protocols," in *WPMC*, vol. 3, Oct. 2002, pp. 976–980.

[73] W. Su, S. Lee, D. A. Pados, and J. D. Matyjas, "Optimal power assignment for minimizing the average total transmission power in hybrid-ARQ Rayleigh fading links," *IEEE Trans. Commun.*, vol. 59, no. 7, pp. 1867–1877, July 2011.

[74] T. V. K. Chaitanya and E. G. Larsson, "Outage-optimal power allocation for hybrid ARQ with incremental redundancy," *IEEE Trans. Wireless Commun.*, vol. 10, no. 7, pp. 2069–2074, July 2011.

[75] Y. Abdallah, M. A. Latif, M. Youssef, A. Sultan, and H. El Gamal, "Keys through ARQ: Theory and practice," *IEEE Trans. Inf. Forensics Security*, vol. 6, no. 3, pp. 737–751, Sept. 2011.

[76] R. Cam and C. Leung, "Throughput analysis of some ARQ protocols in the presence of feedback errors," *IEEE Trans. Commun.*, vol. 45, no. 1, pp. 35–44, Jan. 1997.

[77] S. M. Kim, W. Choi, T. W. Ban, and D. K. Sung, "Optimal rate adaptation for hybrid ARQ in time-correlated Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 968–979, March 2011.

[78] I. Stanojev, O. Simeone, Y. Bar-Ness, and C. You, "Performance of multi-relay collaborative hybrid-ARQ protocols over fading channels," *IEEE Commun. Lett.*, vol. 10, no. 7, pp. 522–524, July 2006.

[79] D. Tuninetti, "Transmitter channel state information and repetition protocols in block fading channels," in *ITW*, Sept. 2007, pp. 505–510.

[80] J. Perret and D. Tuninetti, "Repetition protocols for block fading channels that combine transmission requests and state information," in *ICC*, May 2008, pp. 1297–1301.

[81] E. Malkamaki and H. Leib, "Performance of truncated type-II hybrid ARQ schemes with noisy feedback over block fading channels," *IEEE Trans. Commun.*, vol. 48, no. 9, pp. 1477–1487, Sept. 2000.

[82] V. K. Oduol and S. D. Morgera, "Performance evaluation of the generalized type-II hybrid ARQ scheme with noisy feedback on Markov channels," *IEEE Trans. Commun.*, vol. 41, no. 1, pp. 32–40, Jan. 1993.

[83] A. Chuang, A. Guillen i Fabregas, L. K. Rasmussen, and I. B. Collings, "Optimal throughput-diversity-delay tradeoff in MIMO ARQ block-fading channels," *IEEE Trans. Inf. Theory*, vol. 54, no. 9, pp. 3968–3986, Sept. 2008.

[84] S. Sesia, G. Caire, and G. Vivier, "Incremental redundancy hybrid ARQ schemes based on low-density parity-check codes," *IEEE Trans. Commun.*, vol. 52, no. 8, pp. 1311–1321, Aug. 2004.

[85] B. Makki, A. Graell I Amat, and T. Eriksson, "Power allocation in repetition time diversity hybrid automatic repeat request feedback," in *WCNC*, April 2012, pp. 2329–2334.

[86] ——, "HARQ feedback in spectrum sharing networks," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1337–1340, Sept. 2012.

[87] A. Chelli and M.-S. Alouini, "On the performance of hybrid-ARQ with incremental redundancy and with code combining over relay channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 3860–3871, Aug. 2013.

[88] K. D. Nguyen, L. K. Rasmussen, A. Guillen i Fabregas, and N. Letzepis, "MIMO ARQ with multibit feedback: Outage analysis," *IEEE Trans. Inf. Theory*, vol. 58, no. 2, pp. 765–779, Feb. 2012.

[89] A. Chuang, A. Guillen i Fabregas, L. K. Rasmussen, and I. B. Collings, "Optimal rate-diversity-delay tradeoff in ARQ block-fading channels," in *ITW*, 2006, pp. 507–511.

[90] E. Uhlemann, L. K. Rasmussen, A. Grant, and P. Wiberg, "Optimal incremental-redundancy strategy for type-II hybrid ARQ," in *ISIT*, 2003, p. 448.

[91] K. D. Nguyen, L. K. Rasmussen, A. Guillen i Fabregas, and N. Letzepis, "MIMO ARQ systems with multi-level feedback," in *ISIT*, 2009, pp. 254–258.

[92] L. Szczecinski, C. Correa, and L. Ahumada, "Variable-rate transmission for incremental redundancy Hybrid ARQ," in *GLOBECOM*, 2010, pp. 1–5.

[93] L. Szczecinski, P. Duhamel, and M. Rahman, "Adaptive incremental redundancy for HARQ transmission with outdated CSI," in *GLOBECOM*, 2011, pp. 1–6.

[94] L. Szczecinski, S. R. Khosravirad, P. Duhamel, and M. Rahman, "Rate allocation and adaptation for incremental redundancy truncated HARQ," *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2580–2590, June 2013.

[95] F. Peng, J. Zhang, and W. E. Ryan, "Adaptive modulation and coding for IEEE 802.11n," in *WCNC*, March 2007, pp. 656–661.

[96] "Mobile WiMAX - part II: A comparative analysis," WiMAX Forum, May 2006.

[97] B. Makki and T. Eriksson, "On the average rate of quasi-static fading channels with ARQ and CSI feedback," *IEEE Commun. Lett.*, vol. 14, no. 9, pp. 806–808, Sept. 2010.

[98] ——, "On fairness, power allocation and optimal channel quantization in multiuser systems utilizing multiple feedback bits," *Eura. J. Wireless Commun. and Net.*, Sept. 2013, accepted, in press.

[99] B. Makki, T. R. Lakshmana, T. Eriksson, and T. Svensson, "On resource allocation in coordinated multi-point networks," *IEEE Trans. Wireless Commun.*, 2013, to be submitted.

[100] B. Makki and T. Eriksson, "Multiuser diversity in correlated Rayleigh-fading channels," *Eura. J. Wireless Commun. and Net.*, vol. 38, 2012.

[101] B. Makki, L. Beygi, and T. Eriksson, "Channel capacity bounds in the presence of quantized channel state information," *Eura. J. Wireless Commun. and Net.*, Dec. 2010, doi:10.1155/2010/495014.

[102] B. Makki, J. Li, T. Eriksson, and T. Svensson, "Throughput analysis for multi-point joint transmission with quantized CSI feedback," in *VTC Fall*, 2012, pp. 1–5.

[103] B. Makki, T. Eriksson, and T. Svensson, "On optimal feedback resource allocation in multiple-input-single-output channels," *IET Commun.*, 2013, to be submitted.

[104] T. M. Cover and J. A. Thomas, *Elements of Information Theory.* Wiley, New Jersey, 2006.

[105] A. Lozano, A. M. Tulino, and S. Verdu, "Optimum power allocation for parallel Gaussian channels with arbitrary input distributions," *IEEE Trans. Inf. Theory*, vol. 52, no. 7, pp. 3033–3051, July 2006.

[106] D. Guo, S. Shamai, and S. Verdu, "Mutual information and minimum mean-square error in Gaussian channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 4, pp. 1261–1282, April 2005.

[107] S. Shamai, "A broadcast strategy for the Gaussian slowly fading channel," in *ISIT*, 1997, p. 150.

[108] Y. Liu, K. N. Lau, O. Y. Takeshita, and M. P. Fitz, "Optimal rate allocation for superposition coding in quasi-static fading channels," in *ISIT*, 2002, p. 111.

[109] B. Makki, N. Seifi, and T. Eriksson, "Multi-user diversity with two-step channel state information feedback," *IET Commun.*, vol. 6, no. 9, pp. 1119–1125, 2012.

[110] J. Xu, J. G. Andrews, and S. A. Jafar, "MISO broadcast channels with delayed finite-rate feedback: Predict or observe?" *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1456–1467, April 2012.

[111] R. Bhagavatula and R. Heath, J., "Predictive vector quantization for multicell cooperation with delayed limited feedback," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2588–2597, June 2013.

[112] B. Khoshnevis, W. Yu, and R. Adve, "Grassmannian beamforming for MIMO amplify-and-forward relaying," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 8, pp. 1397–1407, Oct. 2008.

[113] W. Xu, X. Dong, and W. S. Lu, "MIMO relaying broadcast channels with linear precoding and quantized channel state information feedback," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5233–5245, Oct. 2010.

[114] P. de Kerret and D. Gesbert, "Degrees of freedom of the network MIMO channel with distributed CSI," *IEEE Trans. Inf. Theory*, vol. 58, no. 11, pp. 6806–6824, Nov. 2012.

[115] F. Argenti, G. Benelli, and A. Garzelli, "Generalised stop-and-wait protocol," *Elec. Lett.*, vol. 28, no. 9, pp. 861–863, 1992.

[116] C. Pimentel and R. L. Siqueira, "Analysis of the go-back-N protocol on finite-state Markov Rician fading channels," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2627–2632, July 2008.

[117] M. Zorzi and R. R. Rao, "Throughput analysis of ARQ selective-repeat protocol with time diversity in Markov channels," in *GLOBECOM*, vol. 3, 1995, pp. 1673–1677.

[118] D. Chase, "Code combining–a maximum-likelihood decoding approach for combining an arbitrary number of noisy packets," *IEEE Trans. Commun.*, vol. 33, no. 5, pp. 385–393, May 1985.

[119] B. Makki and T. Eriksson, "On the performance of MIMO-ARQ systems with channel state information at the receiver," *IEEE Trans. Commun.*, 2013, submitted.

[120] B. Makki, T. Eriksson, and T. Svensson, "On a relay-ARQ network using adaptive power allocation," *IEEE Trans. Commun.*, 2013, submitted.

[121] B. Makki, A. Graell I Amat, and T. Eriksson, "On noisy ARQ in block-fading channels," *IEEE Trans. Veh. Technol.*, 2013, accepted, in press.

[122] B. Makki, T. Eriksson, and T. Svensson, "On an HARQ-based coordinated multi-point network using dynamic point selection," *Eura. J. Wireless Commun. and Net.*, vol. 2013:209, 2013.

[123] ——, "Spectrum sharing via HARQ feedback and adaptive power allocation," in *WCNC*, 2014, submitted.

[124] B. Makki, J. Li, T. Eriksson, and T. Svensson, "Coordinated multi-point joint transmission using quantized channel state information feedback," in *European wireless*, 2013, pp. 1–5.

[125] M. Zorzi and R. R. Rao, "On the use of renewal theory in the analysis of ARQ protocols," *IEEE Trans. Commun.*, vol. 44, no. 9, pp. 1077–1081, Sept. 1996.

[126] A. El Gamal and Y.-H. Kim, "Lecture notes on network information theory," 2010, [Online]. Available at *http://arxiv.org/abs/1001.3404v4/*.

[127] G. Caire, G. Taricco, and E. Biglieri, "Optimum power control over fading channels," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1468–1489, July 1999.

[128] P. Hesami and J. N. Laneman, "Incremental use of multiple transmitters for low-complexity diversity transmission in wireless systems," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2522–2533, Sept. 2012.

[129] ——, "Low-complexity incremental use of multiple transmitters in wireless communication systems," in *Allerton*, 2011, pp. 1613–1618.

[130] R. A. Horn and C. R. Johnson, *Matrix Analysis*. Cambridge University Press, 1985.

[131] J.-F. Cheng, "Coding performance of hybrid ARQ schemes," *IEEE Trans. Commun.*, vol. 54, no. 6, pp. 1017–1029, June 2006.

[132] H. Boujemaa, "Delays analysis of cooperative truncated HARQ with opportunistic relaying and noisy feedback," in *PIMRC*, Sept. 2010, pp. 1179–1183.

[133] A. Annamalai and V. K. Bhargava, "Analysis and optimization of adaptive multi-copy transmission ARQ protocols for time-varying channels," *IEEE Trans. Commun.*, vol. 46, no. 10, pp. 1356–1368, Oct. 1998.

[134] L. Badia, "On the effect of feedback errors in Markov models for SR ARQ packet delays," in *GLOBECOM*, Dec. 2009, pp. 1–6.

[135] H. Shirani-Mehr, H. Papadopoulos, S. A. Ramprashad, and G. Caire, "Joint scheduling and ARQ for MU-MIMO downlink in the presence of inter-cell interference," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 578–589, Feb. 2011.

[136] R. Huang, C. Feng, and T. Zhang, "Energy efficiency analysis of cooperative ARQ in amplify-and-forward relay networks," in *APCC*, 2011, pp. 197–202.

[137] J. Luo, L. Lin, R. Yates, and P. Spasojevic, "Service outage based power and rate allocation," *IEEE Trans. Inf. Theory*, vol. 49, no. 1, pp. 323–330, Jan. 2003.

[138] K. Chakraborty, S. Dey, and M. Franceschetti, "Service-outage-based power and rate control for poisson fading channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 5, pp. 2304–2318, May 2009.

[139] S. Dey and J. Evans, "Optimal power control over multiple time-scale fading channels with service outage constraints," *IEEE Trans. Commun.*, vol. 53, no. 4, pp. 708–717, April 2005.

[140] T. Kim and J. T. Lim, "Capacity and fairness tradeoff in multiuser scheduling system with reduced feedback," *IEEE Commun. Lett.*, vol. 13, no. 11, pp. 841–843, Nov. 2009.

[141] C.-W. Park, H.-J. Lee, and J.-T. Lim, "Capacity and fairness trade-off in an outage situation over multiuser diversity systems," *IEEE Commun. Lett.*, vol. 15, no. 2, pp. 184 –186, Feb. 2011.

[142] J. W. So and J. M. Cioffi, "Feedback reduction scheme for downlink multiuser diversity," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 668–672, Feb. 2009.

[143] ——, "Capacity and fairness in multiuser diversity systems with opportunistic feedback," *IEEE Commun. Lett.*, vol. 12, no. 9, pp. 648–650, Sept. 2008.

[144] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[145] T. Holliday, A. J. Goldsmith, and H. V. Poor, "Joint source and channel coding for MIMO systems: Is it better to be robust or quick?" *IEEE Trans. Inf. Theory*, vol. 54, no. 4, pp. 1393–1405, April 2008.

[146] K. D. Nguyen, L. K. Rasmussen, A. Fabregas, and N. Letzepis, "Rate-diversity-delay tradeoff for ARQ systems over MIMO block-fading channels," in *AusCTW*, Feb. 2009, pp. 116–121.

[147] F. Berggren, et. al, "Dynamic spectrum access, phase 1: scenarios and research challenges," Sept. 2004, available: http://www.queseth.se/olav/pubs/DSAReportPhase1.pdf.

[148] B. Makki, A. Graell I Amat, and T. Eriksson, "On the robustness of repetition time diversity HARQ in noisy feedback conditions," in *ITW*, 2014, to be submitted.

[149] B. Makki and T. Eriksson, "Interference-free spectrum sharing using a sequential decoder at the primary user," in *SPAWC*, 2012, pp. 154–158.

[150] ——, "On the capacity of Rayleigh-fading correlated spectrum sharing networks," *Eura. J. Wireless Commun. and Net.*, vol. 83, 2011, doi:10.1186/1687-1499-2011-83.

[151] ——, "Secure spectrum sharing via rate adaptation," in *ICNC*, 2013, pp. 1–5.

[152] J. Li, B. Makki, T. Eriksson, and T. Svensson, "Power allocation for multi-point joint transmission with different node activeness," in *WCNC*, 2013, pp. 1–5.

[153] B. Makki and T. Eriksson, "Capacity bounds of spectrum sharing networks with no channel state information," in *European Wireless*, 2011, pp. 1–5.

[154] S. M. Mishra, A. Sahai, and R. W. Brodersen, "Cooperative sensing among cognitive radios," in *ICC*, vol. 4, June 2006, pp. 1658–1663.

[155] S. A. Jafar and S. Srinivasa, "Capacity limits of cognitive radio with distributed and dynamic spectral activity," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 529–537, April 2007.

[156] N. Devroye, M. Vu, and V. Tarokh, "Cognitive radio networks," *IEEE Signal Process. Mag.*, vol. 25, no. 6, pp. 12–23, Nov. 2008.

[157] M. Gastpar, "On capacity under receive and spatial spectrum-sharing constraints," *IEEE Trans. Inf. Theory*, vol. 53, no. 2, pp. 471–487, Feb. 2007.

[158] Y. Xing, C. N. Mathur, M. A. Haleem, R. Chandramouli, and K. P. Subbalakshmi, "Dynamic spectrum access with QoS and interference temperature constraints," *IEEE Trans. Mobile Comput.*, vol. 6, no. 4, pp. 423–433, April 2007.

[159] X. Kang, Y. C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, "Optimal power allocation for fading channels in cognitive radio networks: Ergodic capacity and outage capacity," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 940–950, Feb. 2009.

[160] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 649–658, Feb. 2007.

[161] C.-X. Wang, X. Hong, H. H. Chen, and J. Thompson, "On capacity of cognitive radio networks with average interference power constraints," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1620–1625, April 2009.

[162] L. Musavian and S. Aissa, "Capacity and power allocation for spectrum-sharing communications in fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 148–156, Jan. 2009.

[163] W. C. Ao and K. C. Chen, "End-to-end HARQ in cognitive radio networks," in *WCNC*, 2010, pp. 1–6.

[164] T. Eriksson and T. Ottosson, "Compression of feedback in adaptive OFDM-based systems using scheduling," *IEEE Commun. Lett.*, vol. 11, no. 11, pp. 859–861, Nov. 2007.

[165] V. K. N. Lau, "Proportional fair space-time scheduling for wireless communications," *IEEE Trans. Commun.*, vol. 53, no. 8, pp. 1353–1360, Aug. 2005.

[166] F. Boccardi, F. Tosato, and G. Caire, "Precoding schemes for the MIMO-GBC," in *Int. Zurich Seminar on Commun.*, 2006, pp. 10–13.

[167] A. Wiesel, Y. C. Eldar, and S. Shamai, "Zero-forcing precoding and generalized inverses," *IEEE Trans. Signal Process.*, vol. 56, no. 9, pp. 4409–4418, Sept. 2008.

[168] H. Zhou, P. Fan, and D. Guo, "Joint channel probing and proportional fair scheduling in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3496–3505, Oct. 2011.

[169] S. Schwarz, C. Mehlfuhrer, and M. Rupp, "Throughput maximizing multiuser scheduling with adjustable fairness," in *ICC*, June 2011, pp. 1–5.

[170] L. Yang and M.-S. Alouini, "Performance analysis of multiuser selection diversity," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1848–1861, Nov. 2006.

[171] L. Yang, M. Kang, and M.-S. Alouini, "On the capacity-fairness tradeoff in multiuser diversity systems," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1901–1907, July 2007.

[172] V. Hassel, M.-S. Alouini, D. Gesbert, and G. E. Oien, "Exploiting multiuser diversity using multiple feedback thresholds," in *VTC*, vol. 2, 2005, pp. 1302–1306.

[173] Y. S. Al-Harthi, A. H. Tewfik, and M.-S. Alouini, "Multiuser diversity with quantized feedback," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 330–337, Jan. 2007.

[174] Y. Al-Harthi, A. Tewfik, and M.-S. Alouini, "Opportunistic scheduling with quantized feedback in wireless networks," in *ITCC*, vol. 2, 2005, pp. 716–722.

[175] D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1380–1408, Dec. 2010.

[176] J. Zhang, "Networked MIMO with clustered linear precoding," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1910–1921, April 2009.

[177] C. B. Chae, S. H. Kim, and R. W. Heath, "Network coordinated beamforming for cell-boundary users: Linear and nonlinear approaches," *IEEE J. Sel. Topics Signal Process.*, vol. 3, no. 6, pp. 1094–1105, Dec. 2009.

[178] C. Shen, T. H. Chang, K. Y. Wang, Z. Qiu, and C. Y. Chi, "Distributed robust multi-cell coordinated beamforming with imperfect CSI: An ADMM approach," *IEEE Trans. Signal Process.*, vol. 60, no. 6, pp. 2988–3003, June 2012.

[179] R. U. Nabar, H. Bolcskei, and F. W. Kneubuhler, "Fading relay channels: performance limits and space-time signal design," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1099–1109, Aug. 2004.

[180] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037–3063, Sept. 2005.

[181] T. Cover and A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 572–584, Sept. 1979.

[182] M. Benjillali and L. Szczecinski, "Detect-and-forward in two-hop relay channels: a metrics-based analysis," *IEEE Trans. Commun.*, vol. 58, no. 6, pp. 1729–1736, June 2010.

[183] ——, "A simple detect-and-forward scheme in fading channels," *IEEE Commun. Lett.*, vol. 13, no. 5, pp. 309–311, May 2009.

[184] M. A. Girnyk, M. Xiao, and L. K. Rasmussen, "Optimal power allocation in multihop cognitive radio networks," in *PIMRC*, 2011, pp. 472–476.

[185] M. O. Hasna and M.-S. Alouini, "Outage probability of multihop transmission over Nakagami fading channels," *IEEE Commun. Lett.*, vol. 7, no. 5, pp. 216–218, May 2003.

[186] ——, "Optimal power allocation for relayed transmissions over Rayleigh-fading channels," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1999–2004, Nov. 2004.

[187] ——, "End-to-end performance of transmission systems with relays over Rayleigh-fading channels," *IEEE Trans. Wireless Commun.*, vol. 2, no. 6, pp. 1126–1131, Nov. 2003.

[188] E. Dahlman, S. Parkvall, and J. Skold, *4G LTE/LTE-Advanced for Mobile Broadband*. Academic Press, 2011.

[189] N. Ahmed, M. A. Khojastepour, A. Sabharwal, and B. Aazhang, "Outage minimization with limited feedback for the fading relay channel," *IEEE Trans. Commun.*, vol. 54, no. 4, pp. 659–669, April 2006.

[190] Y. Huang, L. Yang, M. Bengtsson, and B. Ottersten, "A limited feedback joint precoding for amplify-and-forward relaying," *IEEE Trans. Signal Process.*, vol. 58, no. 3, pp. 1347–1357, March 2010.

[191] R. Tannious and A. Nosratinia, "Spectrally-efficient relay selection with limited feedback," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 8, pp. 1419–1428, Oct. 2008.

[192] I. Byun, D. Rhee, Y. J. Sang, M. Kang, and K. S. Kim, "Performance analysis of a decode-and-forward based hybrid-ARQ protocol," in *MILCOM*, Nov. 2008, pp. 1–5.

[193] C. Cheung and R. S. K. Cheng, "Performance analysis for superposition modulated cooperative relay HARQ networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 2978–2990, Sept. 2012.

[194] B. Maham, A. Behnad, and M. Debbah, "Analysis of outage probability and throughput for half-duplex hybrid-ARQ relay channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 3061–3070, Sept. 2012.

[195] J. Li, B. Makki, T. Eriksson, and T. Svensson, "On a relay-ARQ network using adaptive power allocation and space-time coding," *IEEE Trans. Commun.*, 2014, to be submitted.