Non-coherent MIMO Communication for the 5th Generation Mobile: Overview and Practical Aspects

S. Roger, J. Cabrejas, D. Calabuig, J. F. Monserrat, Y. Fouad[*], R. H. Gohary[*], H. Yanikomeroglu[*]
Instituto de Telecomunicaciones y Aplicaciones Multimedia,
Universitat Politècnica de València,
8G Building - access D - Camino de Vera s/n - 46022 Valencia (Spain)
[*] Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario (Canada)
Corresponding author: jomondel@iteam.upv.es

Abstract: Current cellular technologies are based on the concept of coherent communication, in which the channel matrix used for demodulation is estimated via reference or pilot signals. Coherent systems involve a significant increase of the signaling overhead, either when the number of Transmission Points (TP) is increased, due to the use of Coordinated Multipoint transmission/reception (CoMP) with Multiple-Input Multiple-Output (MIMO) processing, or when mobile channel changes rapidly. Another disadvantage of coherent communications is the performance degradation caused by channel estimation errors. Both drawbacks of coherent communication motivate the use of non-coherent techniques. Although there are many theoretical studies on the performance of non-coherent schemes in MIMO systems, their impact on real-world cellular systems is still unknown. This paper focuses on bringing non-coherent techniques into practical systems using CoMP and/or MIMO processing.

Keywords: Non-coherent, MIMO, 5G

1. Introduction

Cellular communication systems are continuously evolving to satisfy the highly increasing user demands. The future information society is expected to support very high data rates in dense crowds of users and in very heterogeneous scenarios. This challenging requirement has triggered the research activities towards the design of 5th Generation mobile networks (5G), where the European Union project Mobile Enablers for the Twenty-twenty Information Society (METIS) is playing a key role [1]. So far, the METIS consortium has identified a set of scenarios and requirements to be addressed by 5G systems. As foreseen by the METIS project, wireless communication systems beyond 2020 will face a large set of requirements and use-cases that cannot be fulfilled solely by existing technologies. Of particular relevance are the needs for providing ten to one hundred times higher average user data rate per cell than today's cellular systems, while improving the energy efficiency and minimizing the cost and spectrum utilization.

It is well known that coherent communications dominate the state-of-the-art of current cellular technologies. Coherent receivers require perfect knowledge of the instantaneous channel variations (i.e., perfect Channel State Information at the Receiver (CSIR)) in order to demodulate the received information. The classical approach to obtain CSIR is to employ training-based channel estimation methods using pilots or reference signals, as done for instance in current LTE-Advanced systems. Pilot-based estimation techniques, however, involve a significant increase of both the receiver complexity and the signaling overhead, especially when the number of Transmission Points (TP) increases due to the use of Coordinated Multipoint transmission/reception (CoMP) schemes with Multiple-Input Multiple-Output (MIMO) processing. For instance, a coherent $M \times N$ MIMO CoMP system requires at least the estimation of $M \times N$ channels, which should be re-estimated every channel coherence time. For this reason, coherent systems are often impractical in fast-fading scenarios, due to their short coherence time. This fact discourages the use of closed-loop transmission modes, which require CSI at the Transmitter side (CSIT), for vehicular users [2]. On the other hand, in slow-fading channels, the transmitter will frequently send pilot symbols, thus leading to wasting some of the resources due to excessive pilot transmissions. Another major disadvantage of coherent communications is their degradation under channel estimation errors, which is especially dramatic under high mobility and, also, when MIMO or CoMP techniques are employed. All the aforementioned drawbacks of training-based communication motivated the increasing research on non-coherent communication techniques, which perform data detection without any knowledge of the channel coefficients at the receiver side [3][4].

The first works on non-coherent communication techniques showed that a careful design of the transmitted signals allows approaching the channel capacity of coherent systems at high signal-to-noise ratios (SNR) [5]. Among the many constellation designs for non-coherent MIMO communication, of particular interest in slow-fading scenarios are the techniques based on differential transmission [6]. To start the communication, a single reference symbol is transmitted, which is normally set to unity, and subsequent symbols are all differentially encoded, each of them based on the symbol in the previous slot. In the framework of non-coherent MIMO systems, Differential Unitary Space-Time Modulation (DUSTM) [6] can be seen as a higher dimensional extension of the standard Differential Phase-Shift Keying (DPSK) modulation to attain non-coherent communication with MIMO channels. In DUSTM, the channel is used in blocks of $T = M$ transmissions, where M stands for the number of transmitting antennas. The transmitted signals belong to a codebook comprising a predefined set of $M \times M$ unitary matrices. The main advantage of DUSTM is its efficient decoding, which can be carried out through Multiple-Symbol Differential Detection (MSSD) at the receiver side [7]. Other alternatives for non-coherent MIMO communication, which are specifically designed for block-fading channels, are codebooks of unitary matrices that are isotropically distributed on the (compact) Grassmann manifold [8][9]. These codebooks exploit the MIMO channel characteristics and consider orthogonal subspaces to differentiate the transmitted symbols at the receiver side. The design of Grassmannian Constellations (GC) is gaining momentum, although so far they have been mainly studied from a theoretical point of view [9]. There exist many designs of GC, some of them systematic [8][10] and others non-systematic [9]. Regarding the decoding of GC, these constellations cannot exploit MSSD due to their non-differential construction. Nevertheless, GC can be non-coherently decoded using generalized likelihood ratio test (GLRT) receivers. Recent works show the utility of GC in Bit-Interleaved Coded Modulation (BICM) systems with Iterative Demodulation and Decoding (IDD) [11][12].

On the other hand, CoMP strategies [13] were identified as key enablers to mitigate inter-cell interference and to increase the cell edge throughput in recently developed standards such as LTE-Advanced [14][15]. If joint transmission from multiple TPs to the same user is assumed, the number of training phases followed by channel estimation stages scales linearly with the number of TPs, since the user needs information of all the channels involved in the transmission to demodulate the received data. The increasing requirements of CSIR availability in CoMP systems and the additional overhead that results from MU-MIMO transmission modes (more than 20% overhead in case of LTE-A with 2 users and 2 layers each [16]) motivates the integration of non-coherent communication modes within state-of-the-art CoMP schemes (see Figure 1(a)). Although these techniques are generally closed-loop, meaning that information about the channel coefficients is necessary at the transmitter side, some recent works claim the need for open-loop CoMP designs to be used as fallback modes in future cellular systems [2]. Figure 1(a) shows an exemplary CoMP architecture where a user has a non-coherent connection with three different TPs. To the best of the authors' knowledge, there are no reported solutions in the literature on how to integrate non-coherent communications with multiuser and/or cooperative systems.

Still focusing on architectures involving multiple TPs, Heterogeneous Network (HetNet) architecture is considered a key element to satisfy the demands of future cellular communications [17]. HetNets may include base stations of varied coverage ranges, as well as multiple frequency bands and radio access technologies for the communication. In this framework, new cellular concepts arise, such as the macroassisted small cell concept referred to as Phantom Cell (PC) [18]. In this kind of cells, the user is connected to the macro and phantom cells simultaneously. The key feature is that control information is delivered by the macro and data flows are delivered by the PC. Note that PCs lack legacy cell-specific signals and, hence, generally have open-loop connections with the users. Therefore, another promising application of non-coherent techniques is their exploitation in novel HetNet architectures, such as those involving PCs without legacy cell-specific signals. Figure 1(b) shows an exemplary HetNet architecture where a user has a coherent connection with the macro-cell and a non-coherent connection with the small cell.

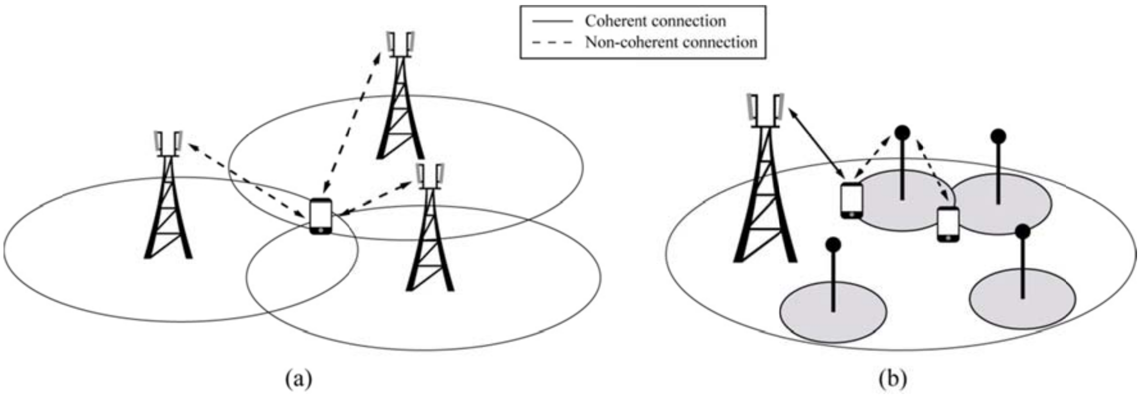

Figure 1. Exemplary architectures for potential application of non-coherent communication: (a) CoMP system, (b) HetNet with macros and small cells.

The remainder of the paper is structured as follows. Section 2 presents an overview of non-coherent MIMO communications, where the system model and some important non-coherent techniques are introduced. Section 3 addresses the use of non-coherent techniques in practical scenarios, such as MIMO systems with antenna correlation and CoMP schemes where the power received by the UE from the different TPs is unbalanced. In Section 4, some performance results on the effect of antenna correlation and unbalanced received power are presented. Finally, some conclusions and future research directions are included in Section 5.

2. Non-coherent MIMO communications

2.1 System model

We consider a MIMO downlink single-user transmission from a set of M antennas, either belonging to the same Base Station (BS) or to a set of coordinated TP, to a User Equipment (UE) with N antennas. The channel block length (number of time slots where the channel coefficients are considered unchanged) is assumed to be T consecutive uses of the channel. During channel block t, we assume a transmission through a channel $\mathbf{H}^{(t)} \in \mathbb{C}^{M\times N}$, containing Gaussian i.i.d. elements with zero-mean and unit-variance, which are unknown at both the transmitter and receiver sides. The signal transmitted through the M antennas during the t-th channel block is represented by the matrix $\mathbf{X}^{(t)} \in \mathbb{C}^{T\times M}$. The possible transmitted matrices are uniformly drawn from a finite-length constellation $\mathsf{C}= \{\mathbf{S}_i, i = 1, \cdots, |\mathsf{C}|\} \subset \mathbb{C}^{T\times M}$, the elements of which have covariance $\mathbf{\Gamma}_\mathrm{X}$ and zero mean. The signal received by the UE, $\mathbf{Y}^{(t)} \in \mathbb{C}^{T\times N}$, is

$$\mathbf{Y}^{(t)} = \sqrt{\frac{\rho T}{\mathrm{Tr}(\mathbf{\Gamma}_\mathrm{X})}}\mathbf{X}^{(t)}\mathbf{H}^{(t)} + \mathbf{Z}^{(t)}, \tag{1}$$

where ρ is the SNR of the received signal and $\mathbf{Z}^{(t)}, \in \mathbb{C}^{T\times N}$ is the additive white Gaussian noise (AWGN) matrix with i.i.d. zero-mean, unit-variance elements.

In the system model (1), the key element is the transmitted matrix $\mathbf{X}^{(t)}$, which must be carefully designed to allow a non-coherent detection at the receiver side. The next two subsections describe several alternatives for the construction of constellations that enable a non-coherent communication.

2.2 Schemes for slowly-varying channels

As stated in the introduction, DUSTM is an extension of the differential phase shift-keying (DPSK) constellation to support systems with multiple transmit and receive antennas. As in every differentially-encoded constellation, each transmitted signal in this scheme works as a reference for the following one. This scheme is intended for slowly-varying channels, where the channel can be assumed constant during any two consecutive channel uses.

In the case of MIMO systems, the codebook of symbols is composed of a set of matrices. A differential modulation scheme based on unitary matrices ($\mathbf{S}_i^\mathrm{H}\mathbf{S}_i = \mathbf{I}$) was proposed in [5], where the signal matrix to be transmitted at time slot t is differentially encoded as:

$$\mathbf{X}^{(t)} = \mathbf{V}^{(t)}\mathbf{X}^{(t-1)}. \tag{2}$$

Here $\mathbf{V}^{(t)}$ belongs to a codebook of $L = 2^{RM}$ unitary diagonal matrices of size $M \times M$, being R the number of bits carried by each diagonal entry. Note that T=M is assumed in this scheme and then $\mathbf{X} \in \mathbb{C}^{M\times M}$. To initialize the communication, $\mathbf{X}^{(0)}$ is considered as an $M \times M$ identity matrix.

The group of $R{\cdot}M$ input bits to be transmitted during M time slots is assigned an index l, which is obtained following a Gray labelling. This index l has a direct correspondence with the element of the codebook of $\mathrm{V}^{(\mathrm{t})}$ matrices that must be selected. The set of $\mathbf{V}$ matrices can be constructed in a cyclic way starting from $\mathbf{V}_1$, which gives the first element of the codebook as:

$$\mathbf{V}_1 = \begin{bmatrix} e^{\frac{j2\pi u_1}{L}} & \cdots & 0 \\ 0 & \ddots & 0 \\ 0 & \cdots & e^{\frac{j2\pi u_M}{L}} \end{bmatrix}, \quad u_m \in \{0,1,\cdots,L-1\}, \;\; m = 1,2,\cdots,M. \tag{3}$$

The rest of elements are subsequently obtained as $\mathbf{V}_l = (\mathbf{V}_1)^l, \; l = 0,\cdots,L-1$. Recall that the transmitted information is contained in the symbol index *l*. Details on how to design the u_m coefficients can be found in [6].

Demodulation requires collecting two successive received matrices to form an equivalent received matrix with *P*= 2*M* rows. With the approximation that the channel is constant during *P* time slots corresponding to two channel blocks, i.e. $\mathbf{H}^{(t)} \approx \mathbf{H}^{(t-1)} = \mathbf{H}$, the received signals in two consecutive blocks are:

$$\mathbf{Y}^{(t-1)} = \sqrt{\frac{\rho T}{\mathrm{Tr}(\boldsymbol{\Gamma}_{\mathrm{X}})}}\mathbf{X}^{(t-1)}\mathbf{H} + \mathbf{Z}^{(t-1)}, \tag{4}$$

$$\mathbf{Y}^{(t)} = \sqrt{\frac{\rho T}{\mathrm{Tr}(\boldsymbol{\Gamma}_{\mathrm{X}})}}\mathbf{X}^{(t)}\mathbf{H} + \mathbf{Z}^{(t)}. \tag{5}$$

Substituting (2) into (5) and combining with (4) we obtain

$$\mathbf{Y}^{(t)} = \mathbf{V}^{(t)}\mathbf{Y}^{(t-1)} + \mathbf{Z}^{(t)} - \mathbf{V}^{(t)}\mathbf{Z}^{(t-1)} = \mathbf{V}^{(t)}\mathbf{Y}^{(t-1)} + \sqrt{2}\mathbf{Z}', \tag{6}$$

which is the fundamental differential receiver equation. Although here the desired signal is corrupted by noise with twice the variance, the channel matrix is no longer necessary for the detection stage. This results in the well-known 3 dB performance loss in effective SNR when the channel is unknown in comparison to when it is known.

2.3 Schemes for block-fading channels

2.3.1 Geometric interpretation

As several studies show [7], at high SNR the coherent capacity in block-fading channels can be achieved if the input signals are isotropically-distributed unitary matrices of size $T \times M$, provided that $T \geq \min\{M, N\} + M$. Following the results in [7], several constellation design methods targeting the high SNR capacity-achieving isotropic distribution were proposed in [8][9]. These unitary matrices can be seen as *M*-dimensional linear subspaces lying inside a *T*-dimensional complex Euclidean space $\mathbb{C}^T$[7]. The columns of the proposed signal matrices form a basis of an *M*-dimensional subspace. Furthermore, each matrix $\mathbf{X}$ is a point in the Grassmann manifold, which is the set of all M-dimensional linear subspaces of $\mathbb{C}^T$. Figure 2 shows an exemplary GC composed of four different directions in a plane, which can be represented by four 2×1 matrices, i.e. four one-dimensional subspaces in a two-dimensional space.

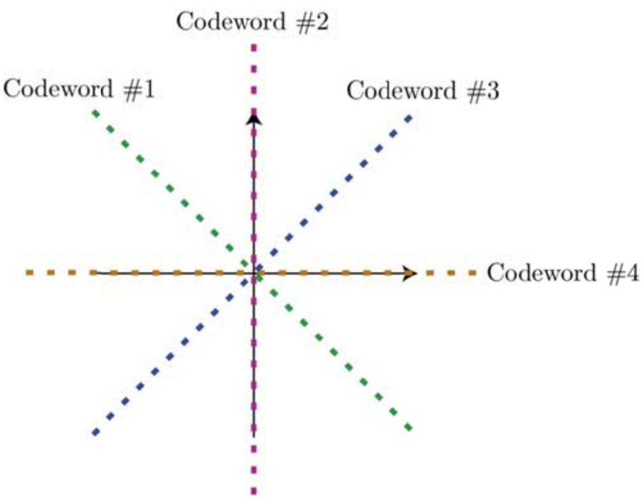

Figure 2. Exemplary Grassmannian codebook for M=1 antenna, T=2 time slots: 4 different directions in a plane.

When the input signal matrix $\mathbf{X}$ is passed through the channel, the column vectors that span the original M-dimensional subspace are rotated and scaled, but they still lie within the same subspace. On the other hand, the noise does affect the subspace, but its effect can be neglected at high SNR. The particular subspace basis rotation is not detectable by a receiver without channel knowledge; however, the M-dimensional linear subspace spanned by this basis can be detected by using a Generalized-Likelihood Receiver Test (GLRT) [8]. The GLRT criterion projects the received signal on the different subspaces that compose the GC. Then, it calculates the energies of all the projections and selects the projection that maximizes the energy as follows

$$\hat{\mathbf{X}} = \arg\max_i \mathrm{Tr}\left(\mathbf{Y}^{\mathrm{H}}\mathbf{S}_i\mathbf{S}_i^{\mathrm{H}}\mathbf{Y}\right). \quad (7)$$

From the perspective of average symbol error probability minimization, in general, the GLRT provides a suboptimal result compared to the Maximum-Likelihood (ML) criterion. However, for the case of unitary codebooks assumed in this work, it can be shown that the GLRT provides ML detection performance [10].

An exemplary procedure for transmission and detection of GC is described next. Figure 3 shows the block diagram of the associated non-coherent transceiver which uses $M = 1$ antenna, $T = 2$ time slots and the GC in Figure 2. First of all, the information bits to be transmitted, x_1 and x_2, are mapped e.g. to Codeword

#3 (see Figure 2). After the codeword is transmitted, its underlying basis (in red) is transformed by the channel, but it remains in the same subspace. Although the non-coherent receiver cannot detect the particular transformation caused by the channel, it can indeed detect the subspace spanned by this basis if $\mathbf{x}h \gg \mathbf{z}$. Therefore, the transmitted information can be recovered without any CSIR.

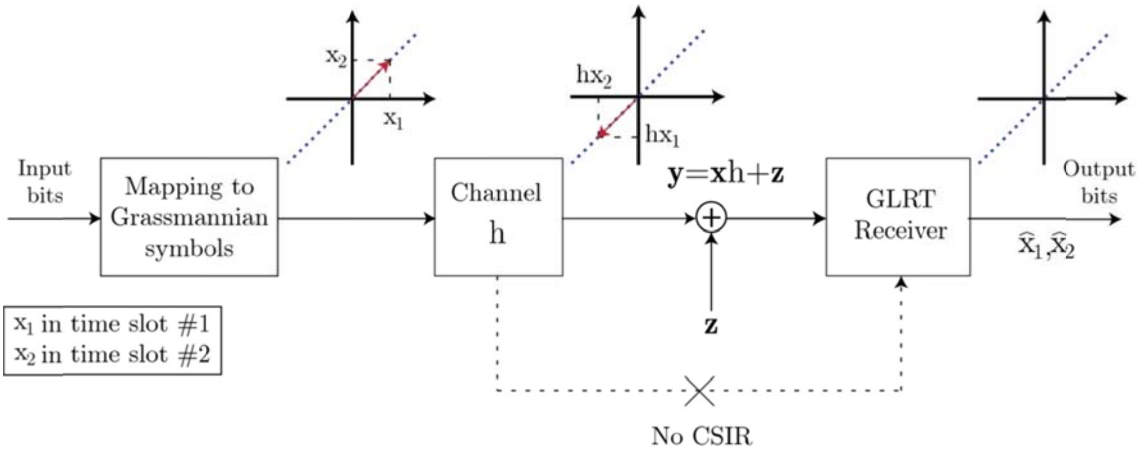

Figure 3. Block diagram of a non-coherent transceiver with *M*=1 antenna and *T*=2 time slots.

2.3.2 Codebook construction

Systematic designs

Most systematic designs of unitary matrices are based on the mapping of a linear Space-Time Block Code (STBC) into a unitary code by means of a certain transformation. One example of these techniques is the code designed in [10], where the exponential transform is applied to a non-unitary codeword matrix $\tau\mathbf{B}$, with τ=0.30, as

$$\mathbf{S}_i = \exp\left\{\begin{pmatrix} 0 & \tau\mathbf{B} \\ -\tau\boldsymbol{B}^H & 0 \end{pmatrix}\right\}\begin{pmatrix} \mathbf{I} \\ 0 \end{pmatrix}, \tag{8}$$

where

$$\mathbf{B} = \begin{pmatrix} s_1 + s_2\zeta_8 & \zeta_{16}(s_3 + s_4\zeta_8) \\ \zeta_{16}(s_3 - s_4\zeta_8) & s_1 - s_2\zeta_8 \end{pmatrix}. \tag{9}$$

For the construction of **B**, the input bits need to be previously grouped and mapped to symbols of a Quadrature Amplitude Modulation (QAM), denoted by s_i. The notation $\zeta_k = e^{\frac{j2\pi}{k}}$ was used in (9).

Another systematic design was proposed in [19], where the first step is to construct a non-unitary codeword $\mathbf{S}_i'$ as

$$\mathbf{S}_i' = \begin{pmatrix} \mathbf{A} \\ \mathbf{B} \end{pmatrix}, \tag{10}$$

where

$$\mathbf{A} = \begin{pmatrix} a_1 + ja_2 & \zeta_8(a_3 - ja_4) \\ \zeta_8(a_3 + a_4) & a_1 - ja_2 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} b_1 + jb_2 & \zeta_8(b_3 - jb_4) \\ \zeta_8(b_3 + b_4) & b_1 - jb_2 \end{pmatrix}. \tag{11}$$

Here the input bits must be mapped to two different constellations with different sizes, one for $\mathbf{A}$ (a_i symbols) and another for $\mathbf{B}$ (b_i symbols). Further details can be found in [19]. Once the non-unitary codeword is constructed, its corresponding unitary matrix is obtained using the QR decomposition, such as $\mathbf{S}_i' = \mathbf{QR}$. The unitary codeword used for transmission is directly $\mathbf{S}_i = \mathbf{Q}$.

The main advantage of systematic codebooks is that they do not need to be stored at the transmitter and at receiver side and only their design rule is necessary. However, their performance is still poorer than the one of the next introduced non-systematic designs.

Non-systematic designs

Non-systematic codebooks are constructed using numerical tools to optimize a certain distance metric on the Grassmann manifold. An overview of distance metrics can be found in [9], where the chordal Frobenius norm between two subspaces was chosen for the design of GC. The chordal Frobenius norm between the two subspaces that are spanned by the columns of two codewords $\mathbf{S}_i$ and $\mathbf{S}_j$ is defined as

$$d^2(\mathbf{S}_i, \mathbf{S}_j) = 2M - 2\mathrm{Tr}\left(\mathbf{\Sigma}_{\mathbf{S}_i^H \mathbf{S}_j}\right), \tag{12}$$

where $\mathbf{\Sigma}_{\mathbf{S}_i^H \mathbf{S}_j}$ is obtained from the SVD decomposition $\mathbf{S}_i^H \mathbf{S}_j = U_{\mathbf{S}_i^H \mathbf{S}_j} \Sigma_{\mathbf{S}_i^H \mathbf{S}_j} V_{\mathbf{S}_i^H \mathbf{S}_j}^H$.

Basically, the constellation design problem consists in selecting unitary matrices with maximum pairwise chordal Frobenius norm between the subspaces they span. The main advantage of these approaches is that it allows exploiting all the system degrees of freedom without restricting the constellation to have a specific structure. However, designing large constellations using a direct optimization may be of prohibitive complexity. Hence, the use of other design methods such as the greedy or rotation-based ones is encouraged [9].

Coherent codes used as a baseline

To prove the interest of non-coherent communication based on GC, these schemes need to be compared to codes designed for the same total number of antennas that need to be coherently decoded (with CSIR). To be consistent with previous works, we will select two coherent (training-based) baselines. In particular, for 2 transmitter antennas, the well-known Alamouti code [20], with the following $T \times M$ code matrix with $T = 2, M = 2$

$$\mathbf{S}_i = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}, \tag{13}$$

and also the Golden code [21], constructed as

$$\mathbf{S}_i = \begin{pmatrix} s_1 + s_2\theta & \gamma(s_3 + s_4\theta) \\ s_3 + s_4\theta & s_1 + s_2\theta \end{pmatrix}, \tag{14}$$

with $\theta = \gamma = e^{j\pi/4}$.

3. Non-coherent schemes in practical scenarios

As previously mentioned, there are many theoretical studies on the design and performance of non-coherent schemes in MIMO systems. However, their impact over real-world cellular systems is still unknown. Before these techniques are mature enough to be considered by wireless communications standards, extensive research on their performance in realistic scenarios must be undertaken. In this direction, we present preliminary results of the performance of non-systematic GC in two realistic scenarios: a MIMO system with spatial correlation and a CoMP system with unbalanced TPs.

3.1 Scenario 1: MIMO system with antenna correlation

In practice, the channels between the different antennas of a MIMO system are often correlated and thus the potential multi antenna gains are not always attainable. This problem is more dominant in mobile terminals due to their compact size.

In this paper, a spatially-correlated Rayleigh block-fading channel is modeled by the Kronecker model [22]. This channel is constant during *T* consecutive channel uses but there exists spatial correlation among the antennas. Hence, the system model in (1) is applicable. This model assumes separable statistics at the transmitter and the receiver and its realizations can be generated from the channel without correlation, **H**, as:

$$\mathbf{H}_{\text{corr}} = \sqrt{\mathbf{R}_{\text{Tx}}}\mathbf{H}\sqrt{\mathbf{R}_{\text{Rx}}}\,, \tag{15}$$

where the channel correlation matrices are modeled in the same way as in [20]

$$\mathbf{R}_{\text{Tx}} = \begin{pmatrix} 1 & \alpha_{12} & \cdots & \alpha_{1M} \\ \alpha_{21} & 1 & \cdots & \alpha_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & 1 \end{pmatrix},\ 0 \le \alpha_{ij} \le 1, \tag{18}$$

$$\mathbf{R}_{\mathrm{Rx}} = \begin{pmatrix} 1 & \beta_{12} & \cdots & \beta_{1M} \\ \beta_{21} & 1 & \cdots & \beta_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{M1} & \beta_{M2} & \cdots & 1 \end{pmatrix},\ 0 \le \beta_{ij} \le 1. \quad (19)$$

Here α_{ij} and β_{ij} are the transmit and receive correlation parameters between the i-th and j-th antennas, respectively. We note that the considered correlation between transmit and receive antennas is assumed to be dual, that is, $\alpha_{ij} = \alpha_{ji}$ and $\beta_{ij} = \beta_{ji}$. Following the usual assumptions, in this paper we consider two antennas are highly correlated when their correlation parameter is equal to 0.7 and low when it is equal to 0.3.

3.2 Scenario 2: CoMP system with unbalanced transmission points

In practical CoMP systems, the UE is rarely located at the same distance from all the TP involved in the transmission. Therefore, the signal is usually received with different power levels. Focusing on the transmission of GC matrices jointly from multiple TPs, we consider that there is a power imbalance among the TP of $0 \le \gamma \le 1$ that weighs the columns (basis) of the transmitted constellation symbol in a different way. For an exemplary GC of 4×2 symbol matrices, which could be transmitted from two TPs with a single antenna each, the original constellation point is composed of two columns, $\mathbf{c}_m \in \mathbb{C}^4$, for m=1, 2

$$\mathbf{S}_i = [\mathbf{c}_1 \quad \mathbf{c}_2], \quad (13)$$

and the unbalanced constellation point is

$$\mathbf{S}_i = \left[\mathbf{c}_1\sqrt{1+\gamma} \quad \mathbf{c}_2\sqrt{1-\gamma}\,\right], \quad (14)$$

where it can be noted that for $\gamma \neq 0$ the subspace basis is no longer orthonormal, it is just orthogonal.

For the performance evaluation, the following power difference among the TP (in dB) will be assumed:

$$\text{Power difference (dB)} = 10 \log\left(\frac{1+\gamma}{1-\gamma}\right). \quad (15)$$

4. Performance evaluation of non-coherent techniques in practical scenarios

We consider a block-fading channel that remains constant during T=4 time slots to evaluate the joint non-coherent communication from 2 TP with a single antenna each, i.e. M=2 transmitter antennas, to a single user with N=2 antennas. The selected codebook is a GC of 4096 points, which leads to a transmission rate of 3 bpcu (12 bits are transmitted in 4 time slots). The GC scheme is compared to two open-loop coherent schemes designed for the same total number of antennas. The coherent baselines are the Alamouti code and the Golden code, the code matrices of which are (13) and (14), respectively.

Provided that M time slots are necessary for training the coherent schemes, 64-QAM and 8-QAM symbols are chosen to set a transmission rate of 3 bpcu in the Alamouti and Golden schemes, respectively. The Alamouti and Golden schemes will be evaluated here under MMSE channel estimation.

4.1 Scenario 1: MIMO system with antenna correlation

We here consider different correlation levels both at the transmitter and at the receiver sides. Figure 4 shows the Block Error Rate (BLER) performance versus SNR of the investigated schemes. It can be observed that, at low SNR, the three evaluated schemes have better performance when $\beta_{12} = 0.7$, hence receiver antenna correlation is beneficial in this scenario. As the SNR gets higher, the setup with $\beta_{12} = 0.3$ achieves better BLER performance for all the schemes. These two results are in concordance with [23] where the authors argue that a fully correlated channel matrix maximizes the mutual information at sufficiently low SNR. In contrast, at high SNR, a fully uncorrelated channel matrix is showed to be optimal. In particular, the crossing point is SNR=22.5 dB for the Alamouti code, SNR=10.2 dB for the Golden code and SNR=7 dB for the GC. Regarding the performance degradation of each individual scheme, for a target $BLER = 10^{-1}$, the Golden code and GC suffer a performance degradation of approximately 2 dB when the receiver antenna correlation is increased. On the other hand, the Alamouti code is quite robust to the receiver correlation, showing a degradation of less than 0.1 dB. The reason for this result may be that, while the Alamouti code can be decoded with acceptable performance using a single receiver antenna, the Golden code and GC require at least two receiver antennas to be correctly decoded. Therefore, keeping the receiver antenna correlation as low as possible is more crucial for the Golden code and GC than for the Alamouti code.

Regarding the comparison among the three investigated schemes, it can be observed a performance gain of 2 dB for GC over Golden codes when $\alpha_{12} = 0.3$ and $\beta_{12} = 0.3$. This gain is also maintained when β_{12} is increased to 0.7. Therefore, in all cases, GC transmission outperforms the coherent baselines.

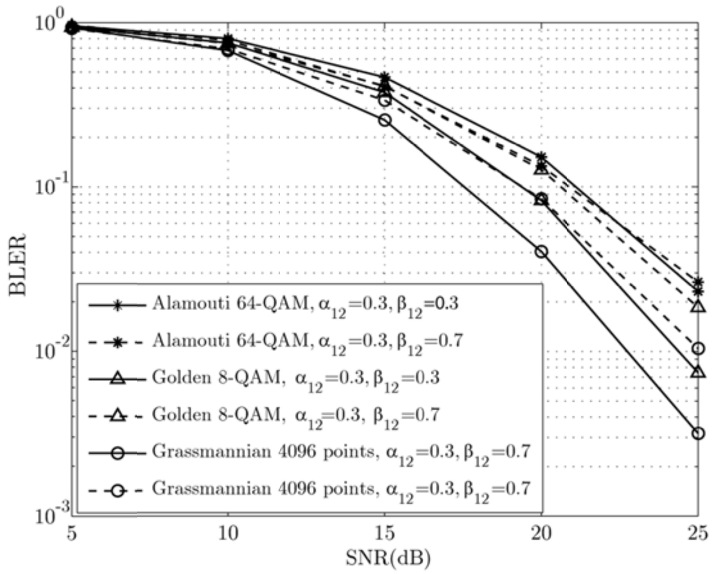

Figure 4. Effects of the spatial correlation over the evaluated coherent and non-coherent schemes for $\alpha_{12} = 0.3$.

In Figure 5, we consider a setup similar to the previous one but with a higher correlation at the transmitter side, given by the value $\alpha_{12} = 0.7$. From this figure, it can be seen that the BLER of all the schemes at low SNR is lower when $\beta_{12} = 0.7$, hence receiver antenna correlation is also beneficial in this scenario. At high SNR, the $\beta_{12} = 0.3$ case is more advantageous, as happened also in the $\alpha_{12} = 0.3$ case. The crossing points are now at SNR=8 dB for the Alamouti code, SNR=16.2 dB for the Golden code and SNR=15 dB for the GC. Regarding the performance degradation of each individual scheme, for a target $BLER = 10^{-1}$, the Golden code and GC suffer a performance degradation of approximately 1 dB, which is half the degradation observed for $\alpha_{12} = 0.3$. The Alamouti code is proven to be more robust to the receiver correlation, showing a degradation of about 0.2 dB. In general, it can be observed that GC-based transmissions outperform the coherent baselines.

Overall, when comparing Figures 4 and 5, it can be seen that the gap between the performance curves decreases as α_{12} increases. As said above, both schemes show cross over points between the curves for high and low receive correlation. Also, by comparing the curves for $\alpha_{12} = 0.3$, $\beta_{12} = 0.7$ with those for $\alpha_{12} = 0.7$, $\beta_{12} = 0.3$ it can be noted that they show the same performance results. Therefore, correlation at the transmitter has the same effect as correlation at the receiver for the three evaluated schemes.

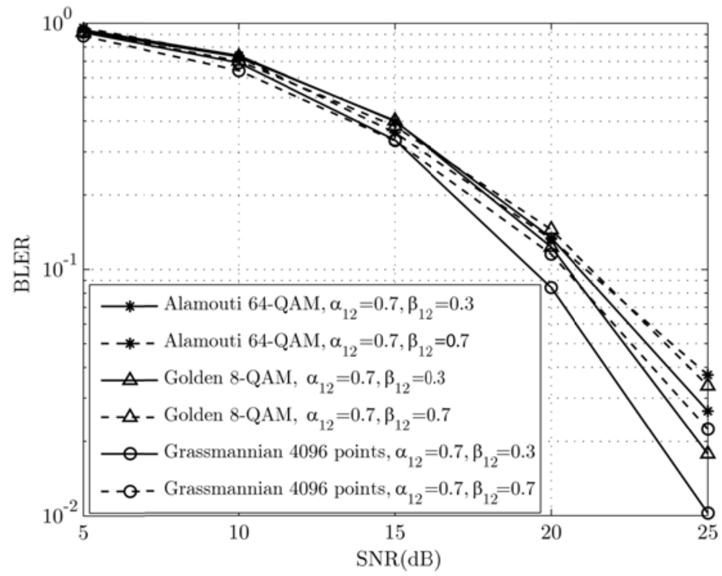

Figure 5. Effects of the spatial correlation over the evaluated coherent and non-coherent schemes for $\alpha_{12} = 0.7$.

4.2 Scenario 2: CoMP system with unbalanced transmission points

Figure 3 shows the BLER of the GC, Alamouti and Golden schemes for an SNR of 20 dB, within a range of values of the power difference among TP. It can be seen that the three schemes are degraded by the power imbalance, but the GC still outperforms the Alamouti and Golden schemes. It is worth noting that more than 17 dB of power imbalance are needed for the GC BLER performance be degraded one order of magnitude. Therefore, subspace transmission is a quite robust scheme within the normal operation range.

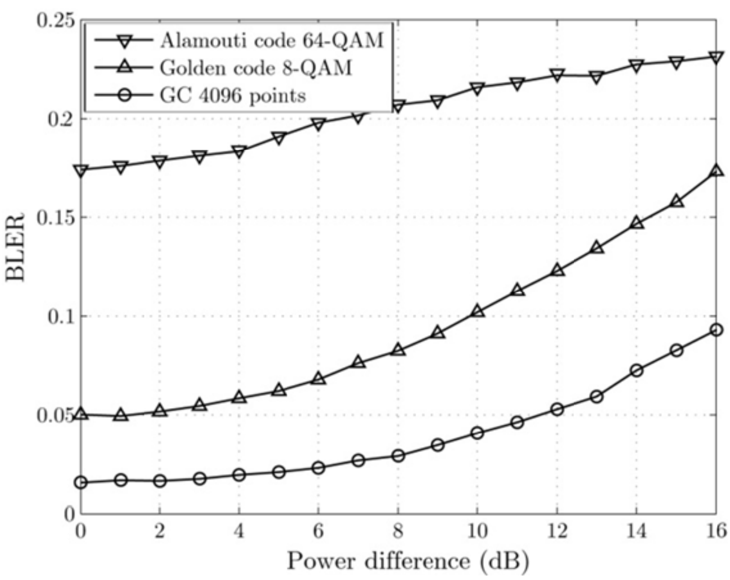

Figure 6. BLER performance of GC, Alamouti and Golden codes at 20 dB of SNR with increasing power difference between two TP.

5. Conclusion

This paper presented concept of non-coherent MIMO communication together with some of the main techniques that enable this type of communication. In addition, we conducted a performance comparison between coherent and non-coherent signalling schemes under practical channel conditions. First, we evaluated the performance of GC and two coherent benchmark schemes, the Alamouti and Golden codes, in a spatially correlated block-fading MIMO system. Despite the fact that spatial correlation is detrimental for coherent and non-coherent systems, the latter outperformed the coherent ones. However, as the correlation between the receive antennas increases, the performance gap between both systems is reduced. Furthermore, we observed that when α_{12} is fixed, the receive correlation coefficient β_{12} tends to improve the system performance at low and moderate values of SNR. On the contrary, correlation between the receive antennas is harmful at high SNR for both systems.

We also evaluated the impact of the power imbalance over the received signal when the user is not at the same distance from all the TP involved in the cooperative transmission. The three evaluated schemes (Alamouti, Golden and GC) were shown to be slightly degraded by the power imbalance. Nevertheless, GC outperformed the other schemes and its BLER degradation was less than one order of magnitude until 17 dB of power imbalance. Therefore, subspace transmission is robust within a wide range of power imbalance values.

Further work includes investigating constellation designs robust to spatial correlation and power imbalance among TPs. In addition, the design of MU-MIMO techniques for non-coherent coordinated communication will be also included in our way forward. Another relevant aspect to be investigated in future work is how GC could be fitted within an OFDM system.

Acknowledgement

This work was performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues in METIS, although the views expressed are those of the authors and do not necessarily represent the project.

References

[1] B. Timus and M. Fallgren (Editors), "D1.1: Scenarios, requirements and KPIs for 5G mobile and wireless system," ICT-317669-METIS, Project Deliverable, April 2013.

[2] J. Zhang, Y. Zhang, Y. Wang and H. Zhou, "DM-RS Based Open-Loop CoMP in LTE-A System", IEEE 75th Vehicular Technology Conference (VTC Spring), pp. 1–5, May 2012.

[3] L. Hanzo, M. El-Hajjar, and O. Alamri, "Near-capacity wireless transceivers and cooperative communications in the MIMO era: evolution of standards, waveform design, and future perspectives," Proc. IEEE, vol. 99, no. 8, pp. 1343–1385, Aug. 2011.

[4] Y. Yang, T.-H. Chang, W.-K. Ma, J. Ge, C.-Y. Chi, and P. C. Ching, "Non-coherent Bit-Interleaved Coded OSTBC-OFDM with Maximum Spatial-Frequency Diversity", IEEE Trans. on Wireless Comm. vol. 11, no. 9, pp. 3335-3347, Sep. 2012.

[5] L. Zheng and D. N. C. Tse, "Communication on the Grassmann Manifold: A Geometric Approach to the Noncoherent Multiple-Antenna Channel", IEEE Trans. on Information Theory, vol. 48, no. 2, pp. 359-383, February 2002.

[6] B. M. Hochwald and W. Sweldens, "Differential Unitary Space-Time Modulation", IEEE Trans. on Communications, vol. 48, no. 12, pp. 2041–2052, December 2000.

[7] T. Cui and C. Tellambura, "Bound-intersection detection for multiple-symbol differential unitary space-time modulation", IEEE Trans. Commun., vol. 53, no. 12, pp. 2114–2123, Dec. 2005.

[8] M. Beko, J. Xavier, V.A.N. Barroso, "Non-coherent Communication in Multiple-Antenna Systems: Receiver Design and Codebook Construction," IEEE Trans. on Signal Processing, vol. 55, no.12, pp. 5703-5715, Dec. 2007.

[9] R. H. Gohary and T. N. Davidson, "Non-coherent MIMO Communication: Grassmannian Constellations and Efficient Detection", IEEE Trans. on Information Theory, vol. 55, no. 3, pp. 1176-1205, March 2009.

[10] I. Kammoun, A. M. Cipriano, and J.-C. Belfiore, "Non-coherent codes over the Grassmannian", IEEE Trans. Wireless Commun., vol. 6, pp. 3657–3667, Oct. 2007.

[11] M. A. El-Azizy, R. H. Gohary and T. N. Davidson, "A BICM-IDD Scheme for Non-Coherent MIMO Communication", IEEE Trans. on Wireless Communications, vol. 8, no. 2, pp. 541-546, February 2009.

[12] R. H. Gohary and T. J. Willink, “On LLR Clipping in BICM-IDD Non-Coherent MIMO Communications”, IEEE Communications Letters, vol. 15, no. 6, pp. 650-652, June 2011.

[13] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, “Multi-Cell MIMO Cooperative Networks: A New Look at Interference”, IEEE Journal of Selected Areas in Communications, vol. 28, no. 9, pp. 1380-1408, December 2010.

[14] J. Lee, Y. Kim, and H. Lee, B. L. Ng, D. Mazzarese, J. Liu, W. Xiao, and Y. Zhou, “Coordinated Multipoint Transmission and Reception in LTE-Advanced Systems”, IEEE Comm. Magazine, vol. 50, no.11, pp. 44-50, November 2012.

[15] X. Tao, X. Xu, Q. Cui, “An Overview of Cooperative Communications”, IEEE Comm. Magazine, vol. 50, no. 6, pp. 65-71, June 2012.

[16] L. Chaiman, Y. Taesang, B Clerckx, L. Byungju, S. Byonghyo, “Recent trend of multiuser MIMO in LTE-advanced”, IEEE Comm. Magazine, vol. 51, no.3, pp.127-135, March 2013.

[17] A. Ghosh, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. A. Thomas, J. G. Andrews, P. Xia, H. S. Jo, H. S. Dhillon, T. D. Novlan, “Heterogeneous Cellular Networks: From Theory to Practice", *IEEE Communications Magazine*, vol 50, no.6, pp. 54-64, June 2012.

[18] T. Nakamura, T. S. Nagata, A. Benjebbour, Y. Kishiyama, “Trends in small cell enhancements in LTE advanced”, *IEEE Communications Magazine*, vol. 51, no.2, pp. 98-105, February 2012.

[19] J.-K. Zhang, F. Huang, S. Ma, “Full Diversity Blind Space-Time Block Codes”, IEEE Trans. on Information Theory, vol. 57, no. 9, pp. 6109-6133, September 2011.

[20] S. Alamouti, “A simple transmitter diversity scheme for wireless communications,” IEEE J. Sel. Areas on Commun., vol. 16, pp. 1451–1458, Oct. 1998.

[21] J.-C. Belfiore, G. Rekaya, and E. Viterbo, “The Golden Code: A 2x2 full rate Space-Time Code with non-vanishing Determinants,” IEEE Trans. on Inf. Theory, vol. 51, no 4, April 2005.

[22] C. Oestges, “Validity of the Kronecker model for MIMO correlated channels,” in IEEE Vehicular Technology Conference, Melbourne, Australia, 7-10 May 2006.

[23] S. G. Srinivasan and M. K. Varanasi, “Optimal Spatial Correlations for the Noncoherent MIMO Rayleigh Fading Channel,” in IEEE Trans. on Wireless Communications, vol. 6, no 10, pp 3760-3769, Oct. 2007.

Biographies

Sandra Roger received the degree in Telecommunications Engineering in 2007, a Master's degree in Telecommunication Technologies, Systems and Communication Networks in 2008 and a PhD in Telecommunications in 2012, all of them from the Universitat Politecnica de Valencia (UPV), Spain. Her Master's thesis was awarded by the Telefonica Chair of the UPV and her Ph.D. dissertation received the second prize of the Algemesi Best Thesis Award. Between 2008 and 2012 she was a PhD grant holder of the Spanish Ministry of Science and Innovation under the Young Faculty Training program FPU. In 2009 and 2010, she was a guest researcher at the Institute of Telecommunications of the Vienna University of Technology (Vienna, Austria), where she worked on several topics related to MIMO wireless communications. Currently, she holds a postdoctoral position at the Mobile Communications group of the Institute of Telecommunications and Multimedia Applications (iTEAM-UPV), where she is involved in the EU project METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society). Her main research interests are in the field of MIMO wireless systems and cooperative communications.

Jorge Cabrejas received his degree in Telecommunications Engineering and Master's degree in Technologies, Systems and Communication Networks from the Universitat Politecnica de Valencia (UPV) in 2008 and 2009, respectively. In 2007 he joined the Mobile Communication Group (MCG) in the Institute of Telecommunications and Multimedia Applications (iTEAM) from the UPV. In 2009, he took part in the best research project granted to the MCG by the Valencia city council. He is currently working on a collaboration project with the company Ingenia Telecom about the mobile networks analysis to optimize the quality delivered to the subscribers. He is also working towards his Ph.D. degree. His research focuses on the study of new mobile communications techniques focusing on non-coherent communications. In 2012, he was a guest researcher at the Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada. He has participated in the WINNER+ project on Advanced RRM techniques for LTE-Advanced.

Daniel Calabuig received the M.S. and Ph.D. degrees in telecommunications from the Universitat Politecnica de Valencia (UPV), Valencia, Spain, in 2005 and 2010 respectively. In 2005 he joined the Institute of Telecommunications and Multimedia Applications (iTEAM) from the UPV. In 2006 he obtained a grant from the Spanish Ministry of Education for helping young researchers obtain their Ph.D. During the following years he participated in some European projects and activities like NEWCOM, COST2100 and ICARUS. Until finishing his Ph.D., Dr. Calabuig worked on radio resource management in heterogeneous wireless systems and Hopfield neural networks optimization. In 2009 he visited the Centre for Wireless Network Design (CWiND) at the University of Bedfordshire, Luton, UK, for a period of four months (CWiND is currently at the University of Sheffield). In 2010 he obtained a Marie Curie Fellowship from the European Commission for researching in the field of cooperative multipoint transmissions. Thanks to this fellowship, Daniel Calabuig visited the department of Systems and Computer Engineering (SCE) at Carleton University, Ottawa, Canada, from 2010 to 2012. During 2012, he also visited the TOBB Ekonomi ve Teknoloji Üniversitesi, Ankara, Turkey, for one month. He is currently involved in the European project Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS), which main objective is laying the foundation of 5G, the next generation mobile and wireless communications system.

Jose F. Monserrat received his MSc. degree with High Honors and Ph.D. degree in Telecommunications engineering from the Universitat Politecnica de Valencia (UPV) in 2003 and 2007, respectively. He was the recipient of the First Regional Prize of Engineering Studies in 2003 for his outstanding student record receiving also the Best Thesis Prize from the UPV in 2008. In 2009 he was awarded with the best young researcher prize of Valencia. He is currently an associate professor in the Communications Department of the UPV. His research focuses on the application of complex computation techniques to Radio Resource Management (RRM) strategies and to the optimization of current and future mobile communications networks, as LTE-Advanced and WiMAX 802.16m. He has been involved in several European Projects, being especially significant his participation in WINNER+ where he leaded the research activities focused on the definition of Advanced RRM techniques for LTE-Advanced and in METIS, where he is the responsible for the simulation activities. In 2010 he participated in an external evaluation group within ITU-R on the performance assessment of the candidates for the future family of standards IMT-Advanced. He co-edited the February 2011 special issue on IMT-Advanced systems published in IEEE Communications Magazine and is co-author of the Wiley book "Mobile and wireless communications for IMT-Advanced and beyond".

Yaser Fouad received his B.Sc. degree in Electronics and Communications Engineering from the Arab Academy for Science and Technology and Maritime Transport, Cairo, Egypt, in 2009. During his studies, he was ranked first across all departments. He then received a M.A.Sc. degree in Electrical and Computer Engineering from Carleton University, Ottawa, Canada, in 2011, where he is currently working toward the Ph.D. degree in Electrical and Computer Engineering. He is currently a research assistant at Carleton University and a member of the Carleton-Huawei research team. His research interests include non-coherent MIMO communication systems, efficient resource allocation in relay-assisted cellular networks, and power allocation techniques in multiuser systems.

Ramy H. Gohary is an adjunct professor and a senior research associate with the Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada. He received the B.Eng. (Hons.) degree from Assiut University, Egypt in 1996, the M.Sc. degree from Cairo University, Egypt, in 2000, and the Ph.D. degree from McMaster University, Ontario, Canada in 2006, all in electronics and communications engineering. From 2006 to 2007, he was a postdoctoral fellow with the McMaster University. He received the Natural Sciences and Engineering Research Council visiting fellowship award in 2007. In 2008 we was a visiting scholar with the Electrical and Computer Engineering Department, of the University of Minnesota, US. From 2008 to 2010, he was a visiting scientist with the Terrestrial Wireless Systems Branch, Communications Research Centre, Canada. From 2010 to 2012, he was the project manager of the Carleton-BlackBerry (formerly Research In Motion (RIM)) research project, and from 2013 to present, he is a member of the Carleton-Huawei research team. Dr. Gohary has co-authored in excess of 60 IEEE journal and conference papers. He has been involved in the organization of the IEEE Vehicular Technology Conference (VTC), Fall 2010, and the IEEE Signal Processing Advances for Wireless Communications (SPAWC), June 2014. He was also a technical program committee member for the 2013 and 2014 IEEE Wireless Communications and Networking Conference (WCNC). Dr. Gohary's research interests include analysis and design of MIMO wireless communication systems, applications of optimization and geometry in signal processing and communications, information theoretic aspects of multiuser communication systems, and applications of iterative detection and decoding techniques in multiple antenna and multiuser systems. Dr. Gohary is a registered Limited Engineering Licensee (LEL) in the province of Ontario, Canada.

Halim Yanikomeroglu received the B.Sc. degree in Electrical and Electronics Engineering from the Middle East Technical University, Ankara, Turkey, in 1990, and the M.A.Sc. degree in Electrical Engineering (now ECE) and the Ph.D. degree in Electrical and Computer Engineering from the University of Toronto, Canada, in 1992 and 1998, respectively. He was with the R&D Group of Marconi Kominikasyon A.S., Ankara, Turkey, during 1993–1994. Since 1998 Dr. Yanikomeroglu has been with the Department of Systems and Computer Engineering at Carleton University, Ottawa, where he is now a Full Professor. His research interests cover many aspects of wireless technologies with a special emphasis on cellular networks. Dr. Yanikomeroglu coauthored more than 50 IEEE journal papers, and has given a high number of tutorials and invited talks on wireless technologies in the leading international conferences. In recent years, Dr. Yanikomeroglu's research has been funded by Huawei, Blackberry, Samsung, Communications Research Centre of Canada (CRC), Telus, and Nortel. This collaborative research resulted in about 18 patents (granted and applied). Dr. Yanikomeroglu has been involved in the organization of the IEEE Wireless Communications and Networking Conference (WCNC) from its inception, including serving as Steering Committee Member as well as the Technical Program Chair or Co-Chair of WCNC 2004, WCNC 2008, and WCNC 2014 to be held in Istanbul. Dr. Yanikomeroglu was the General Co-Chair of the IEEE Vehicular Technology Conference Fall 2010 held in Ottawa. Dr. Yanikomeroglu has served in the editorial boards of the IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, and IEEE Communications Surveys & Tutorials. He was the Chair of the IEEE's Technical Committee on Personal Communications (now called, Wireless Technical Committee). He is a Distinguished Lecturer for the IEEE Vehicular Technology Society. Dr. Yanikomeroglu is a recipient of the Carleton University Faculty Graduate

Mentoring Award in 2010, the Carleton University Graduate Students Association Excellence Award in Graduate Teaching in 2010, and the Carleton University Research Achievement Award in 2009. Dr. Yanikomeroglu spent the 2011–2012 academic year at TOBB University of Economics and Technology, Ankara, Turkey, as a Visiting Professor. He is a registered Professional Engineer in the province of Ontario, Canada.