Detect-and-Forward Relaying Aided Cooperative Spatial Modulation for Wireless Networks

Ping Yang, Bo Zhang, Yue Xiao, Binhong Dong, Shaoqian Li, Member IEEE, Mohammed El-Hajjar, Member IEEE, and Lajos Hanzo, Fellow IEEE

Abstract—A novel detect-and-forward (DeF) relaying aided cooperative SM scheme is proposed, which is capable of striking a flexible tradeoff in terms of the achievable bit error ratio (BER), complexity and unequal error protection (UEP). More specifically, SM is invoked at the source node (SN) and the information bit stream is divided into two different sets: the antenna index-bits (AI-bits) as well as the amplitude and phase modulation-bits (APM-bits). By exploiting the different importance of the AI-bits and the APM-bits in SM detection, we propose three low-complexity, yet powerful relay protocols, namely the partial, the hybrid and the hierarchical modulation (HM) based DeF relaying schemes. These schemes determine the most appropriate number of bits to be re-modulated by carefully considering their potential benefits and then assigning a specific modulation scheme for relaying the message. As a further benefit, the employment of multiple radio frequency (RF) chains and the requirement of tight inter-relay synchronization (IRS) can be avoided. Moreover, by exploiting the benefits of our low-complexity relaying protocols and our inter-element interference (IEI) model, a low-complexity maximum-likelihood (ML) detector is proposed for jointly detecting the signal received both via the source-destination (SD) and relay-destination (RD) links. Additionally, an upper bound of the BER is derived for our DeF-SM scheme. Our numerical results show that the bound is asymptotically tight in the high-SNR region and the proposed schemes provide beneficial system performance improvements compared to the conventional MIMO schemes in an identical cooperative scenario.

Index Terms—Cooperative diversity, detect-and-forward relaying, hierarchical modulation, spatial modulation, space-time shift keying.

I. INTRODUCTION

SPATIAL modulation (SM) constitutes an attractive multiple-input multiple-output (MIMO) [1]–[4] scheme, which is capable of exploiting the indices of transmit antennas as an additional dimension invoked for transmitting additional information besides the traditional amplitude and phase modulation (APM) [5]–[12]. Hence, the throughput of the SM scheme is potentially higher than that of the space time codes (STC) [4]. In \((N_t \times N_r)\)-element MIMO downlink transmissions, generally there are more transmit antennas at the base station (BS) than receive antennas at mobile station (MS). Such MIMO systems may be referred to as an asymmetric or an unbalanced MIMO system [13], whose channel matrix is rank-deficient. A promising solution to achieve a high throughput in asymmetric rank-deficient MIMO channels is to restrict the number of active transmit antennas during each channel use to be less than \(N_r\) and then invoking SM. An additional advantage of SM systems is the significant reduction in the number of radio frequency (RF) chains required at the transmitter end. However, SM may be quite sensitive to the channel conditions [14]–[17].

To overcome this problem, based on a philosophy similar to that of the STC-based schemes, relay-aided SM schemes have been proposed in [18]–[24]. More specifically, in [18], a decode-and-forward (DF) relaying aided space time shift keying (STSK) system was proposed where the dispersion-vector is activated based on cyclic redundancy checking (CRC)-assisted error detection. An information guided transmission (IGT) scheme was employed in [19] for carrying out the random selection of the active nodes from the set of candidate relay nodes (RRs) for the sake of achieving a high relay throughput. However, these systems may focus on single-antenna based transmission at the source-node (SN) and the employment of inter-relay synchronization (IRS) should be considered. Furthermore, in [20], an amplify-and-forward (AF)-relaying-aided space shift keying (SSK) scheme was conceived for reducing the number of transmit antennas and for mitigating the effects of deep fading.

More recently, Mesleh et al. [21],[22] invoked dual-hop AF and DF relaying aided SSK schemes and the corresponding bit error ratio (BER) performance upper-bounds were derived. However, SSK constitutes a special instantiation of SM and only employs the antenna indices for conveying information. As a result, the throughput of the above-mentioned cooperative SSK schemes remains somewhat limited. To eliminate this impediment, a dual-hop cooperative SM scheme [23] was conceived for com-

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P. Yang, Y. Xiao, B. Dong, and S. Li are with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China 611731, Sichuan, China. P. Yang is also with the School of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, U.K. (e-mail: yplw@163.com, {xiaoyue, bhdong, lslq}@uestc.edu.cn).

B. Zhang, M. El-Hajjar, and L. Hanzo are with the School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, U.K. (e-mail: {bzwg10, meh, lh}@ecs.soton.ac.uk).

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bining SSK with classic APM techniques for the sake of transmitting additional bits. However, this scheme does not exploit the benefit of the source-destination (SD) link during the cooperation phase. Furthermore, multiple-antennas are required at the RN, which may not be feasible in practice owing to the space-limitations of the compact shirt-pocket communicators [3]. Moreover, in [24], a SM scheme relying on multiple DF relays was proposed and its error probability performance was derived for transmission over Rayleigh fading channel. Although posed and its error probability performance was derived [24], a SM scheme relying on multiple DF relays was feasible in practice owing to the space-limitations of the antennas are required at the RN, which may not be link during the cooperation phase. Furthermore, multiple- not exploit the benefit of the source-destination (SD) DeF-aided SM scheme assigns the relayed bits flexibly, in order to exploit the spatial dimension of the SD and relay-destination (RD) links. The novel contributions and main results of this paper are as follows.

- In order to attain an improved BER performance, while maintaining a high transmission rate, a DeF relay-aided SM (DeF-SM) scheme is proposed, which relies on a single-antenna aided RN and is capable of operating in asymmetric MIMO channels. This enables us to avoid the employment of multiple RF chains and mitigates the IRS requirements. Furthermore, this scheme may be readily extended to other special cases, such as the scenario of \( N_t \leq N_r \). More importantly, the proposed scheme is capable of achieving a beneficial cooperative diversity gain.

- By considering the different importance of the AI-bits and of the APM-bits, we propose three simple relay protocols as the partial, the hybrid and the hierarchical modulation (HM) [25] based DeF relaying arrangements. In these schemes, the relay re-modulates the message using an appropriately chosen modulation scheme, which may be different from the SM scheme of the SN. As a result, the resultant DeF-SM is capable of striking a flexible tradeoff in terms of the achievable BER, complexity and unequal error protection (UEP) [26], [27]. Moreover, by exploiting the benefits of our low-complexity relaying protocols and inter-element interference (IEI) model, the destination node (DN) is capable of jointly detecting the signal received from the SD and RD links using the proposed low-complexity maximum-likelihood (ML) detector. In order to further reduce the detection complexity imposed, CRC-assisted error detection can be invoked by the RD link.

- Moreover, an upper-bound of the DeF-SM scheme’s BER is derived. Our numerical results show that the bound is asymptotically tight in the high-SNR region and the proposed scheme is capable of achieving a beneficial cooperative diversity gain. Furthermore, it is demonstrated that the proposed cooperative DeF-SM scheme outperforms both the identical-throughput cooperative orthogonal space-time block code (OSTBC) and the SSK-based schemes of [18].

The organization of the paper is as follows. Section II presents our DeF-SM system model and its detection algorithm employed at the DN. Our bounds derived for DeF-SM are presented in Section III, while the corresponding performance comparisons are provided in Section IV. Finally, Section V concludes this paper.

Notation: \((\cdot)^*, (\cdot)^T\) and \((\cdot)^H\) denote conjugate, transpose, and Hermitian transpose, respectively. Furthermore, \(\| \cdot \|\) stands for the Frobenius norm and all logarithms are base of 2.

II. SYSTEM MODEL OF COOPERATIVE DEF AIDED SM

This section describes our cooperative DeF-SM scheme. As depicted in Fig. 1, we consider a two-phase relaying network, which consists of a single SN, a RN and a DN. However, due to their physical size limitations, the number of antennas at the RN and DN is assumed to be one. By contrast, \( N_t \) antenna elements are assumed to be available at the SN. We note that the proposed scheme may be readily extended to the multiple antenna aided DN scenario. Moreover, if multiple relays are considered, the relay-switching action of [3] may be adopted for achieving a further spatial diversity gain. We also assume that each node is operated in a half-duplex mode and a time division multiple access (TDMA) protocol [1] is used. Again, CRC-assisted error detection [1]–[3] is invoked at the RN and DN. It should also be mentioned that although we do not consider explicit channel coding here, our framework may also be readily applied to channel-coded SM bits.

A. Source Model

During the broadcast phase of Fig. 1, the SN firstly attaches the CRC-bits to the information bits for the potential detection of errors at the RN. Then the CRC-encoded bits \( b \) of the SN are mapped to the SM symbols. Let us assume that the SN transmits the vector of symbols \( X_S(i) = [x_1(i), \ldots, x_n(i), \ldots, x_U(i)]^T \), where \( i \) is the transmission block index. The modulated symbol vector is transmitted to both the RN as well as to the
DN. Let \( \mathbb{C} \) denote the field of complex numbers. Then, the transmitted SM symbol \( x_u(i) \in \mathbb{C}^{N_x \times 1} \) is given by \( x_u(i) = s^u e_q \) [5], where \( s^u \) is the complex-valued symbol of the APM scheme employed at the \( q \)th transmit antenna. For example, \( L\)-QAM is associated with \( \log(L) \) input bits, while \( e_q \in \mathbb{C}^{N_x \times 1} (1 \leq q \leq N_l) \) is selected from the \( N_l \)-dimensional standard basis vectors (i.e., \( e_1 = [1, 0, \cdots, 0] \)), according to \( \log(N_l) \) input bits. Hence, a total of \( \log(N_l) \) bits are transmitted in each SM symbol. The corresponding signals received both at the RN as well as the DN are given by

\[
Y_{SR}(i) = H_{SR}(i)X_S(i) + N_R(i), \quad i = 1, \cdots, I
\]

and

\[
Y_{SD}(i) = H_{SD}(i)X_S(i) + N_D(i), \quad i = 1, \cdots, I
\]

respectively. Here, the elements of the channel matrix \( H_{SR} \) and \( H_{SD} \) obey the complex-valued Gaussian distributions of \( \mathcal{CN}(0, \sigma_{SR}^2) \) and \( \mathcal{CN}(0, \sigma_{SD}^2) \), respectively. Moreover, the components of \( N_R \) and \( N_D \) are complex-valued Gaussian random variables obeying \( \mathcal{CN}(0, N_0) \), where \( N_0 \) denotes the noise variance. During the broadcast phase, \( U \)-length symbol blocks are successively transmitted.

**B. HM-based Relay Model**

During the cooperative phase of Fig. 1, the RN relies on CRC-activated DeF transmissions [6]. More specifically, if any detection errors are identified by the CRC, the RN refrains from relaying the signals to the DN and the SN retransmits the corresponding frame during the broadcast phase. By contrast, if the RN flawlessly detects the received signals \( Y_{SR}(i) \) of (1), it re-modulates the detected bits using diverse relaying schemes. For example, the perfectly detected and hence retransmitted bits of the RN may be conveyed to the DN by using an \( L \)-APM scheme, which may be different from the APM scheme adopted at the SN for SM. As a further benefit, because only a single antenna is utilized at the RN, the employment of multiple RF chains and tight IRS can be avoided. In this treatise, we consider HM-based DeF and its simplification forms: the partial and hybrid relaying schemes [7].

By considering the different detection importance of the AI-bits and the APM-bits [15], the DeF-SM is capable of flexibly configuring the relaying protocol. However, as we will show in Section III, the BER of the AI-bits and the APM-bits is only slightly different from each other for most cases in conventional SM. On the other hand, speech, audio and video streams exhibit unequal sensitivity for the different bits, hence UEP-aided transceivers are required for multimedia communications [27]. To this end, our DeF-SM can be readily combined with HM at the RN. More specifically, if the RN correctly detects the received bits, it may re-modulate these bits by using the classic HM method detailed in [26] for adjusting the BER of the subchannels using an appropriate constellation design for matching different UEP requirements. Again, as noted in [26], UEP is beneficial for wireless multimedia services and has been studied in the context of conventional APM [27]. For the sake of providing UEP in SM, the Hamming-distance aided spatial constellation was appropriately adjusted for an SSK scheme in [28]. However, as mentioned in Section I, this SSK-based scheme requires a large number of transmit antennas and yet, its throughput is limited. Furthermore, no cooperative diversity was considered in [28].

Let us continue by first considering an example to introduce the principle of HM. An example of 4/16-QAM HM relying on Gray mapping [25] is illustrated in Fig. 2. The base bits can be viewed as the ones to be mapped to the virtual 4-QAM constellation points of the base symbols in each quadrant. Such a constellation can be defined by two distance parameters: \( d_{0} \) and \( d_{1} \), as illustrated in Fig. 2. These parameters are related to the constellation shaping parameter \( \lambda = d_{1}/d_{0} \). Note that the value range of \( \lambda \) is 0 \( \leq d_{0}^{\min} < \lambda < d_{1}^{\max} \leq d_{0}^{\max} \Rightarrow +\infty \).

\[
0 \leq d_{0}^{\min} < \lambda < d_{1}^{\max} \leq d_{0}^{\max} \Rightarrow +\infty.
\]

Here, \( d_{0}^{\min} \) and \( d_{0}^{\max} \) represent the minimum and maximum values of \( d_{0} \), while \( d_{1}^{\min} \) and \( d_{1}^{\max} \) are the minimum and maximum values of \( d_{1} \). Assuming that the constellation points of the base bits are given by the set \( S_4-QAM \), the twin-layer HM 16-QAM symbols are generated as

\[
S_{HM,16-QAM} = \alpha(S_4-QAM \pm \sqrt{2}\beta e^{j\pi/4}),
\]
where $\alpha = 1/\sqrt{1 + 2\beta^2}$ is the power normalization factor and $\beta = d_0/2$. In a unit-power 16-QAM constellation, we have $d_0 + d_1 = \sqrt{2}$ and the relationship between $\beta$ and $\lambda$ is

$$\beta = \frac{d_0}{2} = \frac{d_0}{\sqrt{2(d_0 + d_1)}} = \frac{1}{\sqrt{2}(\lambda + 1)}. \quad (5)$$

This HM constellation generation method can be extended to other QAM schemes, as detailed in [26]. Note that by varying $\lambda$, which changes the minimum-distance (MMD) property of the classic square-QAM constellation, we may degrade the average BER of the overall modulated bits. However, for these non-uniformly spaced constellations, the receiver becomes capable of recovering at least the more important bits at an acceptable BER even under poor channel conditions. By contrast, the less important bits are only recovered under better channel conditions. Hence, our HM-based DeF-SM scheme is capable of meeting different UEP requirements for both the AI-bits and for the APM-bits. Moreover, upon exploiting the benefits of cooperation, the average BER degradation encountered at the DN remains limited for diverse $\lambda$ values, as detailed in Section IV. More importantly, the classic MMD-based QAM constellation remains an integral part of our HM-based DeF-SM schemes, which is associated with $\lambda = 1$. Based on these observations, we may strike a flexible tradeoff in terms of the average BER of the overall transmitted bits as well as the UEP capability of the AI-bits and APM-bits in our DeF-SM scheme.

Our HM-based schemes can be further simplified when only a fraction of the transmit bits is remodulated at the RN. To be specific, we introduce two special cases of the HM-based DeF arrangement, namely the partial and hybrid DeF Relaying.

1) Partial DeF Relaying: In our SM-based system the information bits can be divided into two sets: the AI-bits and the APM-bits. In partial DeF relaying the RN can only detect and forward one of these two sets. This partial DeF (P-DeF) processing invoked at the RN results in two scenarios.

- P-DeF I: If the RN correctly detects the transmit antenna indices as part of the symbol vector $X_S(i)$ in the cooperative phase, the RN only forwards the AI-bits to the DN, where the corresponding symbols are given by

$$x_{RD}(i) = \begin{cases} x_{ant}(i) & \text{if the AI bits are correctly detected} \\ 0 & \text{if the AI bits are incorrectly detected} \end{cases} \quad (6)$$

- P-DeF II: If the RN correctly detects the APM symbols of the symbol vector $X_S(i)$, the RN only forwards the APM-bits to the DN during the cooperative phase. The corresponding symbols are given by

$$x_{RD}(i) = \begin{cases} x_{APM}(i) & \text{if the APM-bits are correctly detected} \\ 0 & \text{if the APM-bits are incorrectly detected} \end{cases} \quad (7)$$

Here, $x_{ant}$ represents the complex-valued APM symbol relying on $L = N_t$ for re-modulating the AI-bits at the RN, while $x_{APM}$ is the APM symbol associated with $L = L$ for re-modulating the detected APM-bits.

2) Hybrid DeF Relaying: In order to achieve a high spatial diversity gain, a hybrid DeF (H-DeF) relaying scheme may be conceived, which forwards the AI-bits plus either all or a fraction of the APM-bits from the RN. This H-DeF relaying scheme creates subsets containing all the AI-bits and the log $(L')$ number of APM-bits from the SN. This selection is based on the fact that the AI-bits are slightly more vulnerable than the APM-bits in terms of the BER of SM-based systems, as shown both in [17] as well as in Section IV. In the cooperative phase, the RN only forwards the bits in the appropriately chosen subset. For example, given $N_t = 4$ for 16-QAM-assisted SM at the SN, each combined symbol of SM conveys 6 input bits, which contains 4 APM-bits. In the classic 16-QAM constellation, these four bits may be further divided into two different types, as the lower-BER QAM bits and the higher-BER QAM bits, as detailed in [26]. Based on this classification, the hybrid DeF-based relay detects and forwards one of the three subsets: the AI-bits and the two lower-BER QAM bits; the AI-bits and the two higher-BER QAM bits; the AI-bits and all the four QAM-bits. As shown in Fig. 1, the bits to be forwarded by the RN are mapped to a single-antenna APM vector as

$$x_{RD}(i) = \begin{cases} x_{ant-APM}(i) & \text{if the bits are correctly detected} \\ 0 & \text{if the bits are incorrectly detected} \end{cases} \quad (8)$$

3) If all the source bits are retransmitted and remodulated, the RN has to utilize $(L - N_t)$-APM for its transmissions, as detailed in the proposed HM-based DeF-SM scheme.
where $x_{\text{ant+APM}}(i)$ is the complex-valued symbol of conventional ($L = L' \cdot N_t$)-ary APM.

It can be readily shown that our P-DeF and H-DeF schemes constitute special cases of the HM-based DeF arrangement created by adjusting the parameter $\lambda$. For example, the P-DeF I is the HM-based DeF scheme associated with $\lambda \rightarrow +\infty$, when the AI-bits are used as the base bits and the APM-bits are viewed as the refinement bits.

Having generated the HM signal at the single-antenna RN $x_{\text{RD}}(i)$, the signal received at the DN becomes

$$Y_{\text{RD}}(i) = h_{\text{RD}}(i)X_{\text{RD}}(i) + N_{\text{RD}}(i),$$

(9)

where the RD channel coefficients $h_{\text{RD}}(i)$ and the noise $n_{\text{RD}}(i)$ obey the complex-valued Gaussian distributions of $\mathcal{CN}(0, \sigma_{\text{RD}}^2)$ and $\mathcal{CN}(0, N_0)$, respectively. Moreover, $X_{\text{RD}}(i)$ is the transmit vector constituted by $x_{\text{RD}}(i)$.

C. Simplified Joint ML Detection at the DN

In our DeF-SM, the RN should jointly detected both the SD signals of (2) and the RD signals of (9) for achieving a beneficial cooperative diversity gain. In [30], an optimal single-stream ML detector was proposed for conventional SM systems. Here, we extend it to the cooperative DeF-SM receiver by exploiting our low-complexity relaying protocol and the IEI system model at the SN [31], [32]. With the added benefit of relaying, typically a good BER performance is expected.

Our joint DeF-SM detection model relies on combining the signal of the broadcast phase in (2) and that of the cooperative phase in (9), which may be expressed as

$$\hat{Y}(i) = \begin{bmatrix} Y_{\text{SD}}(i) \\ Y_{\text{RD}}(i) \end{bmatrix} \in \mathbb{C}^{(N_t+1)\times 1},$$

(10)

where we have

$$\hat{H}(i) = \begin{bmatrix} H_{\text{SD}}(i) & 0 \\ 0 & h_{\text{RD}}(i) \end{bmatrix},$$

(11)

$$\hat{X}(i) = \begin{bmatrix} X_{\text{S}}(i) \\ X_{\text{RD}}(i) \end{bmatrix},$$

(12)

$$\hat{N}(i) = \begin{bmatrix} N_{\text{D}}(i) \\ N_{\text{RD}}(i) \end{bmatrix}. \quad \text{(13)}$$

Then, similarly to the detection algorithm proposed in [18] and [32], the optimal ML detector of our DeF-SM scheme may be formulated as

$$\hat{b} = \begin{cases} \hat{b}_{\text{RD}} & \text{if the RD signal is correctly detected} \\ \hat{b}_{\text{joint}} & \text{else} \end{cases} \quad \text{(18)}$$

where

$$\hat{b}_{\text{RD}} = D(Y_{\text{RD}}(i)/h_{\text{RD}}(i)),$$

(19)

Here, $D(\cdot)$ denotes the demodulation function and $x^T$ represents the constellation points used at the RN. Hence, the detection complexity may be reduced to

$$C_{\text{CRC-based}} = C_{\text{joint}} \cdot P_{\text{RN-\text{ac}}}(\rho) + C_{\text{RN-\text{DN}}} \cdot [1 - P_{\text{RN-\text{ac}}}(\rho)],$$

(20)

where $C_{\text{RN-\text{DN}}} = 4\overline{L}/\log(N_t L)$ is the complexity of the single-antenna aided detection of (9) and $P_{\text{RN-\text{ac}}}(\rho)$ is the error probability at the DN detector, when the RN is active. We will show in Section III-B that the value of $P_{\text{RN-\text{ac}}}(\rho)$ is low at high SNRs and hence the detection complexity of $C_{\text{CRC-based}}$ is significantly lower than that of $C_{\text{joint}}$ in (17). In conclusion, a high-reliability and low-

$^4$The proposed P-DeF, H-DeF and HM-based DeF may be selectively used or combined depending on the channel conditions and on the detection capability at the RN. However, this adaptive scheme requires the RN to send the side-information of the selected relaying protocol to the DN for achieving a correct joint detection, which requires extra resources. On the other hand, efficiently combining these protocols for exploiting the benefits of cooperation is a challenging problem, which will be investigated in our further studies.

$^5$The use of CRC-checking in RD links may increase the system overhead. As a result, there is a tradeoff between the complexity and the system overhead. In general, this overhead is limited in practical systems.
complexity DN detection may be utilized at high SNRs for carrying out the final detection encapsulated in (14) in the majority of cases. Note that if only a fraction of the transmitted bits is forwarded by the RN operating under the P-DeF and H-DeF schemes, we can also simplify the joint detection of (14). More specifically, we can divide the detection of the DeF-SM scheme into specific scenarios. For example, if the DN only detects the AI-bits received from the RD link correctly, the active antenna indices of SM can be correctly detected. Then we only have to demodulate the signal of the SD link at this detected antenna and calculate the corresponding APM signal. The corresponding detection algorithm can be found in [31]. By contrast, if the DN correctly detects the APM-bits received from the RD link, the signal of the SD link is only used for the detection of the active antennas, as detailed in [6].

III. Theoretical Analysis

Having introduced our DeF-SM scheme in Section II, let us now derive its analytical performance. Here, first we evaluate the average bit error probabilities (ABEPs) of both the AI-bits and of the APM-bits of conventional SM and exploit their difference. Then, the performance of DeF-SM based on joint ML detection is analyzed.

A. ABEPs of the AI-bits and the QAM-bits of SM

The analytical studies disseminated in [5]–[10] exploited some of the fundamental properties of SM related to the channel’s correlation, transmit diversity, channel estimation errors and coding gain. The relationship between the AI-bits and the APM-bits was characterized by an improved union-bound framework in [17], which divides the ABEP of SM into three terms: the $P_{\text{spatial}}$ term related to the AI-bits, the $P_{\text{signal}}$ term related to the APM-bits and the joint term $P_{\text{joint}}$, which depends on both the spatial signal and on the APM signal. However, this framework does not separately quantify the ABEPs of the AI-bits and of the APM-bits. Based on [17], we now derive initial estimations of the above-mentioned ABEPs for exploiting their relationship.

We will mainly focus our attention on the system’s performance for transmission over i.i.d. Rayleigh fading channels. Let us assume that $\rho$ is the average signal to noise ratio (SNR), while $x_t$ and $x_r$ represent two different APM constellation points and their modulus values given by $\beta_t$ and $\beta_r$, respectively. The improved upper union bound of SM is given by [17]

$$P_{\text{SM}}(\rho) \leq P_{\text{spatial}}(\rho) + P_{\text{signal}}(\rho) + P_{\text{joint}}(\rho),$$  \hspace{1cm} (21)

where we have

$$P_{\text{signal}}(\rho) = \frac{\log(L)}{\log(N_t \cdot L)} P_{\text{APM}}(\rho),$$  \hspace{1cm} (22)

$$P_{\text{spatial}}(\rho) = \frac{\log(N_t) N_t}{2L \log(N_t \cdot L)} \sum_{l=1}^{L} W(\rho \beta_t^2).$$  \hspace{1cm} (23)

Here, $P_{\text{APM}}(\rho)$ is the error probability of conventional $L$-APM, which depends on the Euclidean distance of the constellation points of APM. Moreover, the function $W(\alpha)$ is the pair-wise error probability (PEP) function [33], which may be formulated as

$$W(\alpha) = \gamma(\alpha)^{N_r} \sum_{n=0}^{N_r-1} \left( \binom{N_r - 1 + n}{n} \right) [1 - \gamma(\alpha)]^n ,$$  \hspace{1cm} (24)

where we have $\gamma(\alpha) \approx \frac{1}{2} \sqrt{1 - \frac{2}{\sqrt{\beta_t^2}}}$. In order to express the ABEPs of the AI-bits and of the APM-bits, we divide the error probability $P_{\text{joint}}(\rho)$ into two parts as

$$P_{\text{joint}}(\rho) = P_{\text{joint}}^{\text{ant-bits}}(\rho) + P_{\text{joint}}^{\text{APM-bits}}(\rho),$$  \hspace{1cm} (25)

where we have

$$P_{\text{joint}}^{\text{ant-bits}}(\rho) \approx \frac{1}{L \log(N_t \cdot L)} \sum_{l=1}^{L} \sum_{\substack{|i| \neq |j| \leq L}} \left[ \left( \frac{N_t \log(N_t)}{2} \right) W(\frac{2}{\beta_t^2 + \beta_r^2}) \right],$$  \hspace{1cm} (26)

$$P_{\text{joint}}^{\text{APM-bits}}(\rho) \approx \frac{1}{L \log(N_t \cdot L)} \sum_{l=1}^{L} \sum_{\substack{|i| \neq |j| \leq L}} \left[ \left( \frac{N_t \log(N_t) \rho}{L} \right) W(\frac{2}{\beta_t^2 + \beta_r^2}) \right] D_H(x_t \rightarrow x_j) W(\frac{2}{\beta_t^2 + \beta_r^2}).$$  \hspace{1cm} (27)

In (27), $D_H(x_t \rightarrow x_j)$ is the Hamming distance between the APM signals $x_t$ and $x_j$. When considering the number of bits mapped to the AI and to the APM symbol, the ABEPs of the AI-bits and the of APM-bits may be expressed as

$$P_{\text{ant-bits}}(\rho) \approx \frac{\log(N_t \cdot L)}{\log(N_t)} \left( P_{\text{joint}}^{\text{ant-bits}}(\rho) + P_{\text{spatial}}(\rho) \right),$$  \hspace{1cm} (28)

$$P_{\text{APM-bits}}(\rho) \approx \frac{\log(N_t \cdot L)}{\log(L)} \left( P_{\text{joint}}^{\text{APM-bits}}(\rho) + P_{\text{signal}}(\rho) \right).$$  \hspace{1cm} (29)

Considering the parameters $D_H(x_t \rightarrow x_j)$ and $\log(N_t)$, for the conventional SM transmission schemes [5], [17], in most cases, we may arrive at

$$P_{\text{joint}}^{\text{ant-bits}}(\rho) \approx P_{\text{joint}}^{\text{APM-bits}}(\rho).$$  \hspace{1cm} (30)

From (21)-(30), we may infer the following observations:

- (1) If the signal correlation of the transmit antennas is high, $N_t$ is much larger than $L$ and the value of $N_r$ is small, $P_{\text{spatial}}(\rho)$ may be higher than the values of both $P_{\text{joint}}^{\text{ant-bits}}(\rho)$ and $P_{\text{signal}}(\rho)$. Hence we have $P_{\text{ant-bits}}(\rho) > P_{\text{APM-bits}}(\rho)$, which implies that the AI-bit errors dominate the performance of SM.

6To expound a little further, $P_{\text{joint}}$ depends both on the AI-bits and on the APM-bits. As indicated in Eqs. (4), (7) and (16) of [17], we may divide the overall error probability into two parts, which are related to the AI-bits and the APM-bits.

7We note that the SM’s ABEP of Eq. (21) is derived for all the $(\log(L \cdot N_t))$ transmitted bits, which contains $(\log(N_t))$ AI-bits and $(\log(L))$ APM-bits. As detailed in [17], the derived $P_{\text{spatial}}(\rho)$, $P_{\text{signal}}(\rho)$ and $P_{\text{joint}}(\rho)$ probabilities have been weighted by the factor $(\log(L \cdot N_t))$. As a result, when we only calculate the ABEPs of the AI-bits and the APM-bits, the weights $(\log(L \cdot N_t))/\log(N_t)$ and $(\log(L \cdot N_t))/\log(L)$ have to be considered in (28) and (29), respectively.
• (2) By contrast, if $L$ is much larger than $N_t$, $P_{\text{signal}}(\rho)$ may be higher than $P_{\text{joint}}(\rho)$ and $P_{\text{ant}}(\rho)$. Hence $P_{\text{APM}}(\rho) > P_{\text{joint}}(\rho)$ is observed, which implies that the APM-bit errors dominate the performance of SM.

• (3) For most cases, $P_{\text{signal}}(\rho)$ and $P_{\text{spatial}}(\rho)$ are lower than $P_{\text{joint}}(\rho)$ and $P_{\text{ant}}(\rho)$, because when calculating $P_{\text{joint}}(\rho)$ and $P_{\text{ant}}(\rho)$ we have to consider more PEP cases, as seen in (26) and (27). Thus, $P_{\text{joint}}(\rho)$ and $P_{\text{ant}}(\rho)$ are close to each other and hence the conventional SM scheme fails to provide UEP for the AI-bits and for the APM-bits.

We can also explain the above-mentioned effect (1) from the perspective of the constellation design. To be specific, $N_t$ is much larger than $L$, then most of the information bits are conveyed by the antenna indices and the error is dominated by the estimation of the antenna indices, which is affected by the spatial constellation, constituted by the columns of the channel matrix. However, when the value of $N_t$ is small, the $N_r$-element constellation space becomes more crowded. Therefore, by introducing more legitimate spatial elements in an already crowded space may significantly degrade the performance of antenna estimation. Moreover, if $L$ is much larger than $N_t$, the second term of Eq. (29) may be large, hence the APM-bits may dominate the performance of SM. For most cases, $P_{\text{ant}}(\rho)$ and $P_{\text{APM}}(\rho)$ are close to each other. Hence we conceived a HM-based relaying protocol for flexibly creating the number of re-modulated bits and hence the degree of protection provided for the bits.

B. ABEP of the DeF-SM scheme

Based on the ABEP performance of SM in (21), we would like to find the ABEP for our DeF-SM. For reasons of simplicity and clarity, we conceive a two-step analysis model relying on our the CRC-assisted error estimation at the RN. To be specific, an error occurring in the DN’s detector may be categorized into two classes, depending on the state of the RN. The first is when detection errors occur at the DN, while the RN is active (denoted by $P_{\text{Coop}}(\rho)$) and the second one is when errors occur at the DN, while there are detection errors at the RN and hence the RD link was deactivated (denoted by $P_{\text{Coop}}(\rho)$). Then, the overall ABEP can be bounded as follows

$$P_{\text{all}}(\rho) \leq P_{\text{Coop}}(\rho) + P_{\text{Coop}}(\rho),$$

where we have

$$P_{\text{Coop}} = \left(1 - P_{\text{SN-RN}}(\rho) \right) \cdot \frac{P_{\text{HM}}(\rho)}{P_{\text{SM}}(\rho)},$$

Here, $P_{\text{SN-RN}}(\rho)$ and $P_{\text{SN-DN}}(\rho)$ are the ABEPs of the SR and SD links for the conventional SM during the broadcast phase respectively, while $P_{\text{HM}}(\rho)$ is the ABEP of RD link during the cooperative phase when using HM.

Note that if the RN is disabled, the SN retransmits the symbol during the cooperative phase, hence the detector’s SNR at the DN is doubled, because the symbol of the SN is transmitted twice at the same power and the SD channel is constant during the broadcast and cooperative phases, hence the ABEP of the SD link becomes $P_{\text{SN-DN}}(2\rho)$. As seen in Section III-A, the ABEPs of SM can be readily calculated. The approximate BER expressions of HM schemes have been investigated in [34]. As a special case of HM, the BER performance of generalized QAM and PSK constellations has been characterized in [33]. Note that there is a fairly complex interaction between the detection of the AI-bits and the APM-bits, when the RD and SD links are considered jointly. Hence it is hard to achieve the tight bound for the BER of these bits separately in our cooperative DeF scenario. This intricate interaction will be detailed in Section IV.8.

Moreover, according to (32), the conventional bit-to-symbol mapping based on the Euclidean distance of the APM constellation points at the RN may turn out to be optimal in terms of minimizing $P_{\text{Coop}}(\rho)$. Hence it may also be optimal for the overall $P_{\text{all}}(\rho)$ expression. In general, as special cases of HM, the conventional Gray-coded MMD QAM may be the best choice for achieving the optimal average BER of all transmitted bits in our RN transmissions as compared to other HM schemes. However, similarly to the non-cooperative SM scheme, the BER of the AI-bits and of the APM-bits evaluated at the RN is fairly similar to each other for most cases in this uniformly spaced MMD QAM assisted DeF-SM. By contrast, our HM-assisted DeF-SM scheme strikes a flexible tradeoff in terms of the achievable BER and UEP capability, as shown in the next Section. It should be pointed out that by considering the throughput-loss caused by half-duplex relaying, the BER performance of DeF-SM may not always be better than that of the conventional SM at the same throughput. However, according the upper bound of (31) and to our simulation results provided in the next section, the proposed scheme is capable of achieving a beneficial diversity gain, while the BER curves of the conventional SM schemes do not exhibit any additional transmit diversity gain.

IV. Simulation Results

In this section, we provide our performance results, comparing different DeF-SM scenarios and diverse cooperative schemes. The simulation setup is based on 4-6 bits/symbol transmissions over independent flat Rayleigh block fading channels. Unless otherwise stated, our DeF-SM scheme retransmits all the CRC-checked bits with the aid of the corresponding Gray-coded MMD QAM, which is a special case of HM. Note that a frequency selective fading channel can be decomposed into orthogonal non-dispersive sub-bands by the orthogonal frequency-division multiplexing

8It is noted that although the proposed cooperative DeF-SM model has a single antenna at the DN, the ABEP bound of (31)-(33) can be used for arbitrary $N_r$, because the BER performance of the SM and of the HM schemes relying on multiple receive antennas can be found in [17] and [34], respectively.
OFDM) technique and the proposed scheme may then be applied within each OFDM subband. Here, the channel gains of our system are $\sigma^2_{S,R} = 8$, $\sigma^2_{S,D} = 1$ and $\sigma^2_{R,D} = 1^9$. The basic system parameters employed in our simulations are summarized in Table 1.

Fig. 3 shows the achievable BER performance of our cooperative DeF-SM scheme, employing the Gray-coded MMD 4-QAM and 16-QAM schemes at the SN and RN respectively, where the throughput is 4 bits/symbol. Here, two different DeF relaying schemes, namely the selective-DeF and the ‘all-DeF’ based relaying scheme are compared. Recall that the selective-DeF scheme forwards the data if and only if the CRC-based error detection does not spot any errors. By contrast, the ‘all-DeF’ scheme forwards the data regardless of the presence or absence of detection errors, which may lead to error propagation effects $^{10}$.

In Fig. 3 we also plotted the BER curve of the corresponding non-cooperative SM scheme. For completeness, we added the theoretical upper bound derived on the basis of (21) and (31). As expected, our CRC-based selective DeF scheme attains a beneficial cooperative diversity gain, hence it outperforms both the ‘all-DeF’ scheme and the non-cooperative scenario. This scheme provides an SNR gain of about 6-10 dB over both the ‘all-DeF’ and the non-cooperative scheme at $\text{BER}=10^{-5}$. Moreover, we note that the BER curves of the ‘all-DeF’ based scheme and the non-cooperative scenario do not exhibit any cooperative diversity gain. Additionally, the theoretical BER bounds of the AI-bits and of the APM-bits determined for non-cooperative SM are added based on (28) and (29). Here, the simulated BER curves of both the AI-bits and of the APM-bits generated for non-cooperative SM are not shown, since they perfectly overlap with the overall BER curve. It is found that the BER of the AI-bits and of the APM-bits is fairly similar to each other.

In Fig. 4, we investigated the achievable BER performance of our selective DeF-aided schemes for different throughputs. We also considered the cooperative 256-QAM modulated G4-STBC and cooperative SSK associated with $N_{t} = 16$ arrangements as benchmarkers in Fig. 4, which had an effective throughput of $m_{\text{all}} = 4$. For $m_{\text{all}} = 6$ bits/symbol, the performance curves of the cooperative G4-STBC and SSK schemes were not considered because the STBC-based arrangement would require an excessive 4096-level modulation order, while

$^9$We also simulated further channel scenarios, such as $\sigma^2_{S,R} = 8$, $\sigma^2_{S,D} = 1$ and $\sigma^2_{R,D} = 4$. It was found that although the corresponding BER curves seen in Figs. 3-8 were shifted to the lower SN regions due to the increased channel gains, the relative performance of the different DeF scenarios and different cooperative schemes remained largely unaffected. Due to the space limitation, these results are not presented here.

$^{10}$Here, the selective-DeF scheme suffers from a transmission rate loss due to the redundancy of the CRC bits compared to both the non-cooperative SM scheme and to the ‘all-DeF’ based cooperative SM scheme. Bearing in mind the assumption of a 16-bit CRC sequence and a 1000-bit transmission frame, the effective code rate is $R = 1000/1016$. This implies that when plotting the CRC-aided curves on an $E_b/N_0$ scale, they would have to be shifted to the right by only 0.068 dB. Hence, the comparison of different transmission schemes in Fig. 3 can also be used for accurately identifying the resultant gain of the CRC-aided scheme. Moreover, the overhead of CRC-checking is typically negligible.

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**Fig. 3.** BER performance of our 4-QAM modulated cooperative DeF-SM system, comparing different DeF relaying schemes, such as the ‘all-DeF’ and the selective DeF scheme. Moreover, for cooperative schemes, the Gray-coded 4-QAM and 16-QAM are employed at the SN and the RN respectively.

**Fig. 4.** Achievable BER performance of different cooperative transmission schemes obeying the architecture of Fig. 1. To be specific, our cooperative DeF-SM schemes with transmission rate $m_{\text{all}} = 4$ and 6 bits/symbol are employed. The corresponding BER results of the 256-QAM modulated cooperative G4-STBC scheme and the cooperative SSK scheme associated with $N_{t} = 16$ are calculated as the benchmarkers. Moreover, the BER curves of the AI-bits and the QAM-bits are also achieved.

---

The SSK-based scheme needs $N_{t} = 64$ transmit antennas for achieving the effective throughput of $m_{\text{all}} = 6$ bits/symbol. Observe in Fig. 4 for $m_{\text{all}} = 4$ that our DeF-SM scheme outperforms the cooperative OSTBC scheme. The main reason behind the OSTBC’s poor performance is the employment of a higher modulation order required for achieving the same throughput as our SM-based scheme, which was predicted from the results characterized in the non-cooperative SM scenario of [17]. Moreover, our DeF-SM scheme also outperforms the cooperative SSK scheme. This is due to the fact that the SSK-based scheme has to employ more transmit antennas at the SN and the
### System parameters of the cooperative DeF-aided SM schemes

<table>
<thead>
<tr>
<th>Cooperative DeF-aided SM</th>
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<tr>
<td>Number of transmit antenna at SN</td>
<td>(N_t=4)</td>
</tr>
<tr>
<td>Number of transmit antenna at RN</td>
<td>(N_{RN}=1)</td>
</tr>
<tr>
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<td>Transmission rate</td>
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<td>Channel gains</td>
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</tr>
<tr>
<td>Detector</td>
<td>Joint ML detector of (14)</td>
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antenna-index detection is a challenge in the \(N_r=1\) dimensional complex received space, as indicated in [7]. The upper bound curves of the proposed DeF-SM schemes were also included in Fig. 4. It can be observed that our bounds formulated in (31) become tighter, as the SNR increases. Moreover, the BER performance curves of both the AI-bits and of the APM-bits were also plotted in Fig. 4. Similarly to the results of the non-cooperative SM scheme, the BER of the AI-bits and of the APM-bits is also close for these MMD-QAM based DeF-SM schemes, as shown in Fig. 4.

Figs. 5 and 6 portray the BER performance curves of our DeF-aided SM schemes relying only on a fraction of the bits received from the SN. More specifically, we consider the P-DeF I scheme and only relay the AI-bits in Fig. 5. By contrast, the P-DeF II scheme is utilized and the RN only relays the APM-bits in Fig. 6. Additionally, the corresponding BER curve of the non-cooperative scheme is also calculated as a reference. Compared to Fig. 4, which investigates the achievable BER performance of our DeF-aided SM relaying all the transmit bits, we found that 1) the AI-bits of SM may be slightly more important than the APM-bits, because the overall BER performance of P-DeF I is better than that of P-DeF II; 2) there is an interaction between the detection of AI-bits and APM-bits at the DN.

To be specific, when the RN only relays the AI-bits, the BER of the corresponding APM-bits is also improved, as shown in Fig. 5. Moreover, in Fig. 6 the RN only relays the APM-bits, but the BER of the corresponding AI-bits is also improved; 3) compared to the MMD-based DeF-SM schemes, both of P-DeF schemes are capable of providing an UEP for the APM-bits and for the AI-bits, as discussed in Section II-B.

As mentioned in Section II-B, the P-DeF schemes constitute special cases of the HM-based DeF arrangements, depending on the particular choice of the parameter \(\lambda\). Observe in Fig. 7 that the HM-based DeF schemes are capable of offering flexible degrees of error protection for both the AI-bits and for the APM-bits, as controlled by the parameter \(\lambda\). It should be pointed out that the framework proposed here can be extended to multi-class UEP. It may also be seen from Figs. 3 and 7 that the DeF-SM scheme relying on Gray-coded MMD 16-QAM at the RN achieves the best overall BER performance, as predicted in Section III-B. However, this MMD QAM-based DeF does not provide an UEP capability for the AI-bits and of the APM-bits, as shown in Fig. 4. By contrast, upon exploiting the relay’s flexibility, our HM-
assisted DeF-SM scheme is capable of striking a flexible tradeoff in terms of the attainable BER and the provision of UEP.

In Fig. 8, we compared the achievable BER performance of our 4-QAM DeF-SM schemes in the presence of CSI errors. The estimated channels are contaminated by the additive Gaussian noise of $\mathcal{CN}(0, w)$ [35], [36] having a power of $w=0$, 0.1, 0.02 + 0.6/$N_0$ as well as 1/$N_0$ in comparison to the average signal power\(^\text{11}\). Observe in Fig. 8 that the BER performance of DeF-SM is degraded upon introducing CSI estimation errors. When the channel estimation error is high, such as $w=0.1$ and 0.02 + 0.6/$N_0$, the BER curves exhibit error floors. This is because the coherent detection scheme is adversely affected by the potential CSI-estimation errors.

Fig. 9 shows the achievable BER performance of our cooperative DeF-SM schemes in conjunction with different channel qualities for all the transmitted bits, when employing a 4-QAM scheme at the SN. For the sake of simplicity, we assume that the sum of the distance $d_{SR}$ between the SN and the RN, as well as that between the RN and the DN, which is represented by $d_{RD}$, is equal to the distance $d_{SD}$ between the SN and the DN. Furthermore, by considering a path-loss exponent of $\alpha$ [37], [38] ($\alpha=3$ is adopted to consider a typical urban area), the average normalized channel power gain $\sigma^2_{ij}$ at the output of the channel can be calculated as $\sigma^2_{ij} = d^{-\alpha}_{ij}$ ($i,j \in \{S, R, D\}$). The normalized distance $d_m = d_{SR}/d_{SD}$ is used for specifying the location of the RN and hence it represented different channel qualities for our DeF-SM scheme. Additionally, the BER curves of the conventional 4 $\times$ 1 BPSK-modulated SM scheme are also provided. Observe in Fig. 9 that considerable BER performance gains can be achieved by our DeF-SM scheme compared to the non-cooperative identical-throughput SM scheme at high SNRs. Moreover, the overall BER performance is better, when the SR link quality is good, similar to the conventional cooperative MIMO schemes of [3], [4]. Based on the results seen in Fig. 9, the RN location may be optimized by using the minimum BER criterion. For example, the optimal distance $d_m = d_{SR}/d_{SD}$ is used to specify the location of RN and hence represented different channel strengths.

\(^{11}\)For example, when the CSI-estimation error variance is 5 dB below the received signal variance, the CSI-estimation SNR is 5 dB.
in Figs. 4 and 9 that the proposed scheme is capable of achieving a higher diversity gain and better BER than the conventional benchmark at medium to high SNRs.

V. CONCLUSIONS

In this paper, we have proposed a novel cooperative SM arrangement, where the CRC-based DeF-aided protocol was conceived for transmission during the cooperative phase. It has been shown in Figs. 3-7 that the achievable performance of our DeF-SM is quite attractive, especially in case of a high throughput. As a further benefit, the employment of multiple RF chains and the requirement of IRS can be avoided. By exploiting our low-complexity relaying protocol and CRC-assisted error detection as well as using diversity combining at the DN, a beneficial scheme was conceived. Furthermore, a BER upper bound was derived for our DeF-SM. The numerical results show that the resultant bound is asymptotically tight in the high-SNR region. Moreover, as a benefit of the relay’s flexibility, our DeF-SM allows us to select the number of re-modulated bits and hence the degree of protection provided for the bits upon combining it with the classic HM technique. Our further work will be focused on the integration of power allocation, non-coherent detection and relay parameter optimization in the context of the proposed scheme.

REFERENCES


Ping Yang received the B.E. and M.E. degrees in 2006 and 2009, respectively from University of Electronic Science and Technology of China (UESTC). Now he is currently pursuing the Ph.D. degree at the same university. His research interests include MIMO systems, space-time coding and communication signal processing.

Bo Zhang received his B.S. degree in Information Engineering from National University of Defense Technology, China, in 2010. He is currently working toward the Ph.D. degree at the same university. His research interests include MIMO systems, space-time coding and communication signal processing.

Yue Xiao received a Ph.D. degree in communication and information systems from the University of Electronic Science and Technology of China in 2007. He is now an associate professor at University of Electronic Science and Technology of China. He has published more than 30 international journals and been involved in several projects in Chinese Beyond 3G Communication R&D Program. His research interests are in the area of wireless and mobile communications.

Binhong Dong received her B.S. degree, M.S degree and Ph.D. degree in Communication and Information Engineering in 1993, 1999 and 2006 from University of Electronic Science and Technology of China, respectively. Her research interests include wireless communication technology and anti-jamming technology in wireless communication.

Shaoqian Li received his B.S.E. degree in communication technology from Northwest Institute of Telecommunication (Xidian University) in 1982 and M.S.E. degree in Communication System from University of Electronic Science and Technology of China (UESTC) in 1984. He is a Professor, Ph.D. supervisor, director of National Key Lab of Communication, UESTC, and member of National High Technology R&D Program (863 Program) Communications Group. His research includes wireless communication theory, anti-interference technology for wireless communications, spread-spectrum and frequency-hopping technology, mobile and personal communications.

Mohammed El-Hajjar is a lecturer in the Electronics and Computer Science in the University of Southampton. He received his BEng degree in Electrical Engineering from the American University of Beirut, Lebanon in 2004. He then received an MSc in Radio Frequency Communication Systems and PhD in Wireless Communications both from the University of Southampton, UK in 2005 and 2008, respectively. Following the Ph.D., he joined Imagination Technologies as a research engineer, where he worked on designing and developing the BICM peripherals in Imagination’s multi-standard communications platform, which resulted in several patent applications. In January 2012, he joined the Electronics and Computer Science in the University of Southampton as a Lecturer in the Communications, Signal Processing and Control research group. He is the recipient of several academic awards and has published a Wiley-IEEE book and in excess of 40 journal and international conference papers. His research interests include machine-to-machine communications, mm-wave communications, large-scale MIMO, cooperative communications and Radio over fiber systems.

Lajos Hanzo FREng, FIEEE, FIET, Fellow of EURASIP, DSc received his degree in electronics in 1976 and his doctorate in 1983. In 2009 he was awarded the honorary doctorate “Doctor Honoris Causa” by the Technical University of Budapest. During his 35-year career in telecommunications he has held various research and academic posts in Hungary, Germany and the UK. Since 1986 he has been with the School of Electronics and Computer Science, University of Southampton, UK, where he holds the chair in telecommunications. He has successfully supervised 80 PhD students, co-authored 20 John Wiley/IEEE Press books on mobile radio communications totalling in excess of 10 000 pages, published 1300 research entries at IEEE Xplore, acted both as TPC and General Chair of IEEE conferences, presented keynote lectures and has been awarded a number of distinctions. Currently he is directing a 100-strong academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) UK, the European IST Programme and the Mobile Virtual Centre of Excellence (VCE), UK. He is an enthusiastic supporter of industrial and academic liaison and he offers a range of industrial courses. He is also a Governor of the IEEE VTS. During 2008 - 2012 he was the Editor-in-Chief of the IEEE Press and a Chaired Professor also at Tsinghua University, Beijing. His research is funded by the European Research Council’s Senior Research Fellow Grant. For further information on research in progress and associated publications please refer to http://www-mobile.ecs.soton.ac.uk.