Full-Duplex MIMO and PLNC for the Y-Network

Filipe E. Ferreira[1,2], Francisco A. Monteiro[1,2], Ivo Sousa[1,3]

[1] Instituto de Telecomunicações, Portugal
[2] ISCTE - Instituto Universitário de Lisboa, Portugal
[3] Instituto Superior Técnico, Universidade de Lisboa, Portugal
francisco.monteiro@lx.it.pt

Abstract — **This paper considers a multi-way wireless network with three terminals which want to exchange or share data with the help of a relay: each terminal has some information that wants to transmit to the other two. The traditional way of doing this exchange either involves time-domain multiplexing (TDMA) or dedicated frequency-domain disjoint channels, at the expense of high bandwidth inefficiency. With the advent of network coding, and later physical-layer network coding, it became possible to reduce the number of time slots required to exchange the information between all the terminals. Moreover, using multiple-input multiple-output (MIMO) terminals and relays, the time-usage efficiency can be further boosted by transferring the burden from the time-domain to the spatial-domain via spatial multiplexing. This paper proposes the concatenation of the aforementioned techniques along with loopback interference cancellation, which recently became a central topic for the next generation of the physical-layer of wireless communications. The paper shows a protocol and techniques that allow all the information exchange between terminals to be reduced from the 6 time-slots, required in traditional TDMA, to one time-slot only, provided that the information packets are not too short. The error performance of this system is shown by means of simulation using MIMO Rayleigh fading channels.**

Keywords— Multi-way channel; full-duplex; interference suppression; MIMO; physical-layer network coding.

I. Introduction

When electromagnetic waves (EM) interfere due to superposition, they naturally produce at the physical layer the sum operation used in network coding. This concept, known as physical layer network coding (PLNC), has been recently studied in order to improve performance on relay communications, while at the same time it is able to use physical-layer functionalities [1]. The PLNC concept is specially suitable to enhance the throughput in the two-way relay channel (TWRC) scenarios [2][3], where two terminals exchange data with the help of a relay, given that they cannot communicate directly. In the traditional TWRC scenario, one terminal would send its message to the relay in the first time slot, the other terminal would use the second time slot for its message and the relay, after applying network coding, would send in the third time slot, the sum of the previously received signals. As the relay only needs the sum of the messages, with PLNC the terminals can transmit their signals simultaneously to the relay, in the same time slot, and the relay would then send this sum of signals in the following time slot, hence reducing the total required number of communication stages to only two time slots [2] [3].

A recent hot topic in signal processing for wireless communications is the use of full-duplex (FD) radios. These offer the possibility of doubling the spectral efficiency of a wireless system by transmitting and receiving data at the same time and in the same frequency band [4]. However, FD techniques suffer from the loopback interference (LI) problem, which means that interference suppression techniques are required. There has been much improvement in combining several techniques (in the antenna domain, natural isolation, radio frequency analog domain, and in the signal processing domain), achieving results that bring the interference noise to the same level of the thermal noise level [5] [6] [7].

The network considered in this paper is referred in the physical layer literature as the Y-channel [8]. It comprises three terminals communicating with each other with the help of a MIMO relay, and can be regarded as a generalized network model of the TWRC for three different users, when the terminals cannot physically establish direct connections between them due, for instance, to EM propagation obstacles or power limitations. Two strategies have been proposed in [9] to reduce the 6 slots required in TDMA to three slots and then two slots only. The goal of this work is to combine all the previously mentioned techniques, namely PLNC and multiple-input multiple-output (MIMO), along with FD, in order to attain the maximum throughput (in terms of channel use) of this wireless network configuration. This paper considers that some interference is suppressed at the physical layer whilst some of it persists and impairs the layer above. Given this cross-layer design with the use of three MIMO terminals and one relay, we refer to this configuration as the Y-network. The strategy proposed in this paper is able to reduce all communication stages to a single time slot per message exchanged on average.

The paper is organized as follows. Section II describes the considered system model. In Section III the proposed strategies for the exchange of information are presented. The performance results obtained through simulation are provided in Section IV, followed by the conclusions in Section V.

II. System Model with Full-Duplex

A. Message Exchanging Protocols

The Y-network adopted in this work is depicted in Fig. 1 for the case of a TDMA operation mode. The relay needs to receive three messages, each of which coming from a different

978-1-5090-0058-6/16/$31.00 ©2016 IEEE

terminal (dashed-red lines) and later needs to broadcast each of them so that each user gets its two remaining messages (solid-blue lines), which in total amounts to 6 time-slots being required.

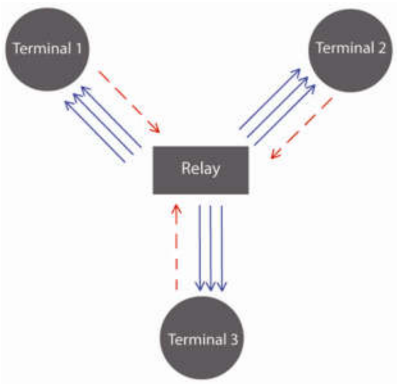


Figure 1: The Y-network configuration with three terminals and one relay.

In the first stage of the multiple-access channel (MAC) phase of the schemes proposed in [9], one creates a virtual-MIMO uplink with three streams (from the terminals to the relay) where the relay receives the incoming symbols from the three terminals using three MIMO antennas. In the new proposed setup, both the relay and the terminals have extra antennas to support FD: the relay is equipped with three receiving antennas and three transmitting antennas, using the so-called natural isolation, RF isolation and signal suppression techniques, and signal processing dealing with the remaining signal cancellation as in [4-7]. On the other side, each terminal has one transmitting antenna and one or two receiving antennas, depending on the chosen configuration (as shown in Fig. 2, Fig. 3 and Fig. 4), also using the same interference suppression techniques to isolate the transmit antenna from the receiving one(s).

In this full-duplex setup, a new phenomenon arises, setting this model apart from the one in [9]: one has to deal with the loop-interference (LI), represented by the dotted lines in Fig. 2, Fig. 3, and Fig. 4.

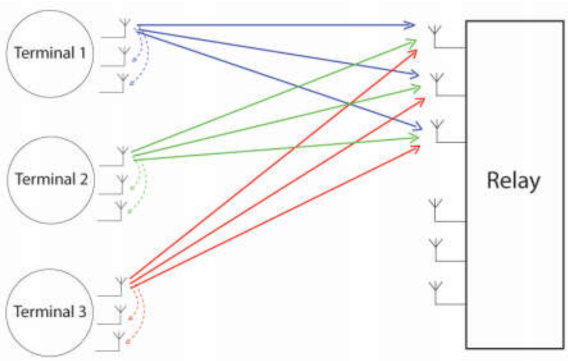


Figure 2. Uplink phase with full-duplex (the third antenna of each terminal is not used in configuration A - cf. Fig. 3).

Two different configurations for the terminals' side will be studied, with the relay's side having three receiving antennas and three transmitting antennas in both configurations. The first configuration, denoted hereafter as configuration A, considers terminals with one receiving antenna and one transmitting antenna, so as to enable FD (Fig. 3).

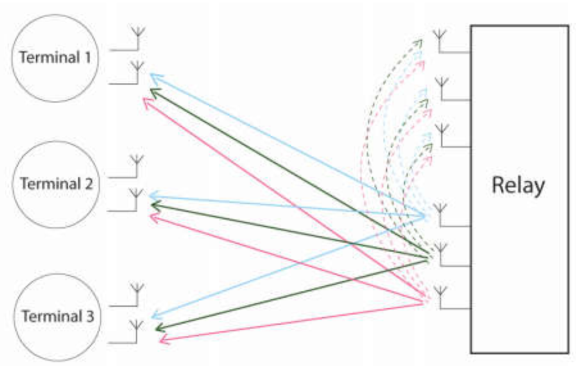


Figure 3. Downlink phase with full duplex (configuration A).

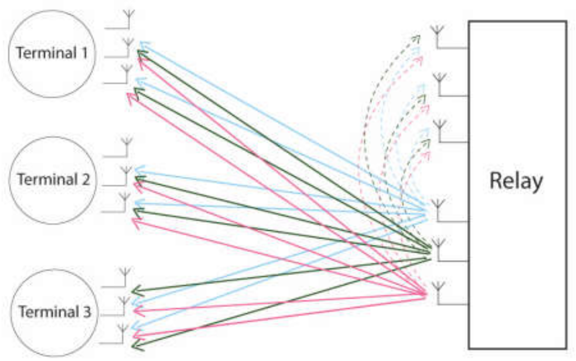


Figure 4. Downlink phase with full-duplex (configuration B).

The second configuration, denoted hereafter as configuration B, comprises the same number of antennas at the relay, but each terminal has now two receiving antennas instead of one (Fig. 4), enabling MIMO detection to be employed in the downlink, detecting two symbols at once (for messages originated at the relay).

The overall process of message exchanges when employing FD with configuration B is depicted in Fig. 5. In this case, the receiver is able to detect the two incoming unknown messages, given that it already knows its own message and can cancel it out using the PLNC principle. The arrows in Fig. 5 are associated to the messages exchanged along the successive time-slots, where $x_{i,j}$ represents a message sent from terminal i during time slot j. Since in the first time-slot the relay does not have anything to send to the terminal, it remains silent. After this initial stage, the transmit antennas at the three terminals and at the relay are all actively sending data streams, resulting on an average of one time-slot per information exchange.

Again, it should be noted the delay of one time-slot in the downlink regarding the information that is sent in the uplink.

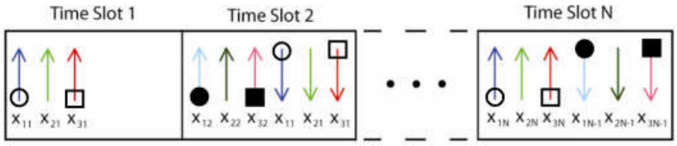


Figure 5. Messages flow between the terminals and the relay using configuration B (terminals with two receiving antennas).

B. Physical Layer Signals and Detection

For a given time slot $n>1$, the signal that the relay receives is given by

$$\mathbf{y}_n = \mathbf{H}_n\mathbf{x}_n + \mathbf{n}_n + \mathbf{H}_{LI,n}\hat{\mathbf{x}}_{n-1} \quad (1)$$

where $\mathbf{y}_n = \left[y_{1,n}, y_{2,n}, y_{3,n}\right]^{\mathrm{T}}$ is the received signal vector, $\mathbf{x}_n = \left[x_{1,n}, x_{2,n}, x_{3,n}\right]^{\mathrm{T}}$ denotes the transmitted signal vector, $\mathbf{H}_n$ stands for the channel matrix where each entry $h_{i,k,n}$ represents the link between the transmitting antenna of the *k*-th terminal and the *i*-th receiving antenna of the relay, $\mathbf{n}_n$ corresponds to the noise vector, $\hat{\mathbf{x}}_{n-1} = \left[\hat{x}_{1,n-1}, \hat{x}_{2,n-1}, \hat{x}_{3,n-1}\right]^{\mathrm{T}}$ denotes the previously detected symbol at the relay and $\mathbf{H}_{LI,n}$ stands for the channel matrix of the LI at the relay. On the other hand, the signal that each terminal receives in the same time slot *n* is given by

$$\mathbf{y}'_n = \mathbf{H}_n\hat{\mathbf{x}}_{n-1} + \mathbf{n}'_n + \mathbf{H}'_{LI,n}\,\mathbf{x}_n \quad (2)$$

where $\mathbf{y}'_n$ represents the received signal vector, $\mathbf{n}'_n$ corresponds to the noise vector and $\mathbf{H}'_{LI,n}$ denotes the channel matrix of the LI at the terminals.

The LI contribution in both (1) and (2) cannot be neglected and leads to a performance loss, hence some type of isolation (physical and electrical) must be added between the corresponding pair transmitting/receiving antenna. In this work, this reduction of the LI will be represented by a new term *K*, with *K*<1, i.e., a lower *K* value represents a higher reduction of the self-interference, yielding the following updated expressions

$$\mathbf{y}_n = \mathbf{H}_n\mathbf{x}_n + \mathbf{n}_n + K\cdot\mathbf{H}_{LI,n}\hat{\mathbf{x}}_{n-1} \quad (3)$$

$$\mathbf{y}'_n = \mathbf{H}_n\hat{\mathbf{x}}_{n-1} + \mathbf{n}'_n + K\cdot\mathbf{H}'_{LI,n}\,\mathbf{x}_n\,. \quad (4)$$

For simulation purposes, each element of the different channel matrices is taken from a zero-mean circularly symmetric complex Gaussian distribution with unit variance and the noise components are drawn from an independent circularly symmetric complex Gaussian with zero average and variance σ_n^2. It is also assumed that the channel state information at the receiver (CSIR) is available and that, as reflected in (3) and (4), all the links between terminals and the relay are reciprocal, i.e., they are the same in the uplink and downlink phases (when this assumption is verified in real systems, it represents an advantage since it simplifies the channel estimation phase). *M*-ary squared quadrature amplitude modulation (*M*-QAM) constellations are used to transmit the different messages. The symbols are taken from a finite complex constellation C constructed from the Cartesian product $\mathrm{C} = \mathrm{C}_R \times \mathrm{C}_R$, where C_R is the real set

$$\mathrm{C}_R = \left\{-\left(\sqrt{M}-1\right), \ldots -3, -1, +1, +3 \ldots, +\left(\sqrt{M}-1\right)\right\}. \quad (5)$$

Without loss of generality, the filters adopted for the performance assessment at the receivers have an impulse response $h(t)$ normalized to $\int |h(t)|^2\, dt = 1$.

Finally, the symbol error rate (SER) of the downlink phase is obtained comparing the messages decoded at each terminal or relay with the original messages sent by each of them in the uplink phase. For the case of the relay the SNR is defined by

$$\mathrm{SNR} = \frac{E\left\{\mathbf{y}_n{}^T\mathbf{y}_n\right\}}{E\left\{\mathbf{n}_n{}^T\mathbf{n}_n\right\} + K^2 E\left\{\hat{\mathbf{x}}_{n-1}^T\mathbf{H}^T{}_{n-1}\mathbf{H}_{LI,n}\hat{\mathbf{x}}_{n-1}\right\}}, \quad (6)$$

as in similar FD systems [10]. Likewise, a similar expression can be written for the terminals' side. Note that the downlink performance accumulates the errors occurred during the two phases, i.e.,

$$\mathrm{SER}_{\mathrm{total}} = 1-(1-\mathrm{SER})^2\,. \quad (7)$$

III. Proposed Strategies

The full-duplex strategies proposed evolve from the ones presented in [9]. With the uplink and downlink phases being transmitted in the same time slot, the overall throughput in terms of channel usage is doubled [9].

Regarding the uplink phase, the same strategy is used for both configuration A and configuration B, using virtual MIMO: the signals are transmitted simultaneously by the three terminals, and the relay applies a robust detection technique such as a lattice reduction-aided (LRA) detector, followed by ordered successive interference cancelation with minimum mean square error (OSIC-MMSE) [11]. As well-known in MIMO literature, the performance attained with LRA captures the full diversity order available in the MIMO spatial multiplexing. After this stage, the MIMO relay has detected the messages x_1, x_2, and x_3. This procedure consumes one time slot in the overall messages exchanging process.

The downlink phase in configuration A consists of the following three steps:

i) the relay first broadcasts the estimates of the signal received during the previous time slot;

ii) then, using the PLNC principle, each terminal receives the above overlapped messages and cancels its own contribution (as they all know which signal they previously transmitted as well as the channel response, given that CSIR is assumed);

iii) finally, each terminal computes estimates of the two remaining messages of the other two terminals using joint detection, i.e., maximum likelihood joint (ML) detection for those two remaining symbols.

During the downlink phase of configuration B, the first cancellation described for configuration A is performed in the same manner at all the three terminals, however, since two antennas are used for reception in configuration B, the remaining detection problem can be seen as a 2×2 MIMO spatial multiplexing problem which can be dealt with by one of the many different detection techniques, according to the complexity-performance tradeoff one needs and is able to afford [11]. For this purpose, LRA OSIC-MMSE was chosen to obtain the results, i.e., the same detection algorithm as the one employed at the relay in the first phase is used. Note that the downlink phase consumes one time slot, independently of the type of configuration used for the terminals.

Consider now the following example, where five messages from each terminal are to be exchanged with the other terminals in the Y-network: the first time slot is solely used for the first uplink phase of data; the second time slot is used for the first downlink phase of data, as well as for the second uplink phase of the messages; this procedure is repeated until the sixth time slot, which is only used for the last downlink phase of information. Hence, six time slots are required for the whole procedure. In general, the downlink phase corresponding to the $(n-1)$-th message uploaded to the relay (in the previous time slot $n-1$) is performed at the same time slot as the uplink phase of the next message (n); thus, the average time required to transmit N messages is $N+1$, and consequently, when N goes to infinity, one obtains a single time slot per exchanged message on average.

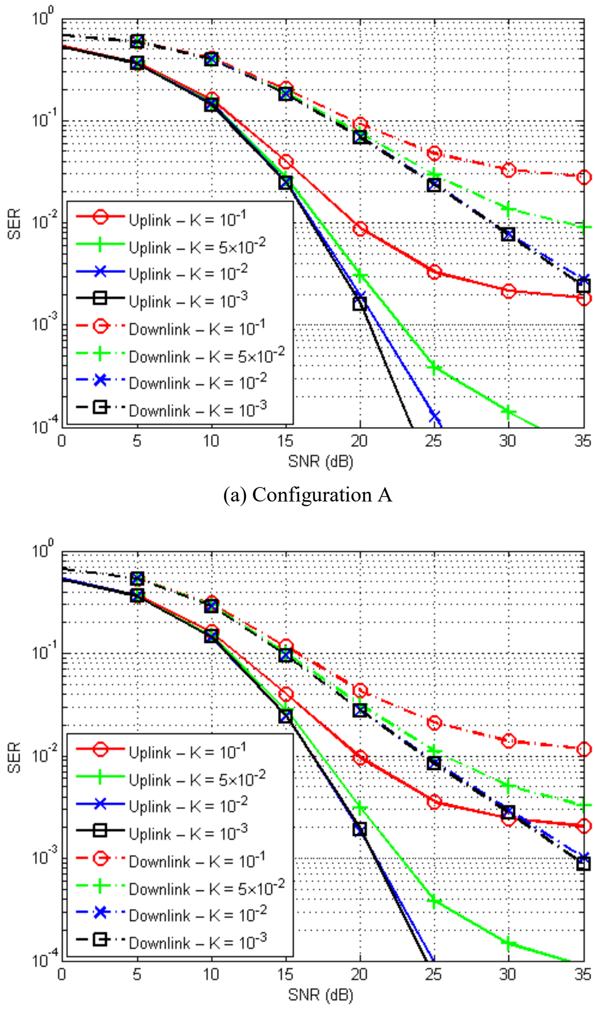
IV. Performance Results

The two strategies evaluated in the paper were simulated with LRA with OSIC-MMSE detection at the relay and at the relays for the MIMO detection stage in configuration B. In addition, ML detection (i.e., brute force) is adopted for configuration A when estimating the two final remaining messages. Fig. 6 and Fig. 7 respectively show the performance results in terms of the overall SER with 4-QAM and 16-QAM, using the same constellations in both the uplink and downlink phases. Note that both schemes achieve the goal of just one time-slot per exchanged message (where 16-QAM obviously achieves a spectrally more efficient system), however, one can conclude from Fig. 7 that, because joint detection is severely impaired in the case of 16-QAM, configuration A can only be used for binary or quaternary alphabets.

One can observe that for a higher K factor (which amounts for the achieved isolation added to the signal processing cancellation gain), the performance deteriorates in all cases, as expected from (3) and (4), and thus, these results quantify how much isolation for full-duplex communication is required for a certain targeted performance. Additionally, the results show that up to a certain SNR value, the performance are quite similar for low values of K (e.g., for SNR < 20 dB and in all cases, the performance is nearly the same whether $K=10^{-2}$ or $K=10^{-3}$). In other words, for applications that do not usually operate at high SNR, one only needs to optimize the LI isolation up to a certain point, allowing a simpler and cheaper concatenation of isolation and LI cancellation methods. This is because in the low SNR regime the interference can essentially be treated as additional (non-removable) noise.

Given that in configuration B the detection at the terminals of the last two remaining symbols is undertaken with special diversity of order two, this configuration surpasses the performance of the A counterpart for the same K factor. This is observed in the figures for configuration B in the downlink phase, by noticing the doubling of the slope of those curves. Nonetheless, this gain comes at the expense of the complexity involved in LRA OSIC-MMSE detection [11].

In the uplink phase the performance is the same for both configurations, since the relay receiving operation does not change. As expected, the performance of the downlink phase is worse than the uplink phase, given that the former accumulates the errors that occur in the uplink and downlink phases - cf. (7).



(a) Configuration A

(b) Configuration B

Figure 6. Performances of the two configurations in the Y-network with 4-QAM in both phases. Symbol error rates at the relay (uplink) and at each of the terminals (uplink followed by downlink).

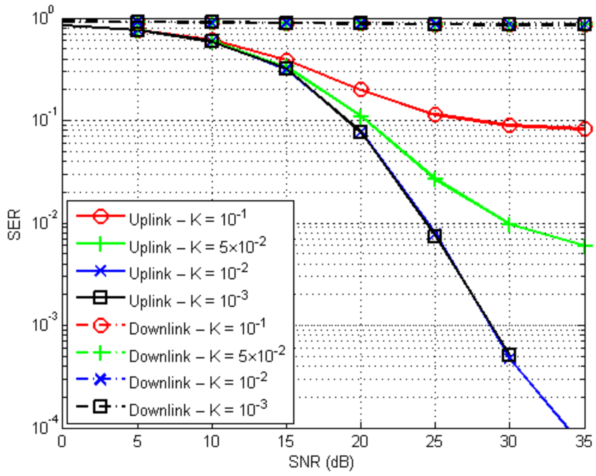
V. Conclusions

This paper proposes the combination of in-band full-duplex physical layer with MAC layer protocols based on physical layer network coding in order to accomplish the exchange of messages in the Y wireless network encompassing tree terminals and one relay. By assessing the performance of the proposed setups for typical levels of residual interference, it was shown that, for good levels of interference cancellation, this phenomenon can be well tolerated whilst allowing doubling the time efficiently of the exchange mechanism in the Y-network, when using MIMO terminals running standard detection algorithms such as lattice-reduction-based ones. By also using MIMO receivers, a sufficient SER performance is still achievable at the terminals (considering that in uncoded wireless links a BER of 10^{-3} is acceptable) with the current loopback interference cancellation techniques. Indeed, for the more demanding 16-QAM modulation, one needs two receive antennas at the terminals, such that the MIMO diversity of order two can separate the two remaining streams after cancelling the terminal's own data.

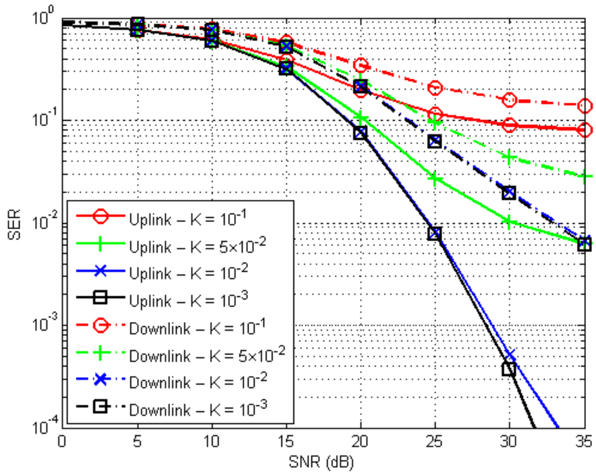
One should note that the complexity involved in putting together the three techniques is no more than the sum of the individual complexity associated to each.

Acknowledgments

This work was funded by FCT (Foundation for Science and Technology) under project UID/EEA/50008/2013. Filipe E. Ferreira was funded by Instituto de Telecomunicações and FCT under project PEst-OE/EEI/LA0008/2013. Francisco A. Monteiro is grateful to the European COST Action IC1104 – "Random Network Coding and Designs over GF(q)" for providing funding and learning opportunities in the field of network coding.



(a) Configuration A



(b) Configuration B

Figure 7. Performances of the two configurations in the Y-network with 16-QAM in both phases. Symbol error rates at the relay (uplink) and at each of the terminals (uplink followed by downlink).

References

[1] P. Hu, M. Ibnkahla, "A survey of physical-layer network coding in wireless networks," in *Proc. of 25th Biennial Symposium on Communications (QBSC)*, pp. 311-314, Kingston, ON, Canada May 2010.

[2] P. Popovski, and H. Yomo, "Physical network coding in two-way wireless relay channels", in *Proc. of 2007 IEEE Inter. Conf. on Communications (ICC)*, pp. 707-712, Glasgow, UK, June 2007.

[3] Y. Wu, P. A. Chou, and S.-Y. Kung, "Information exchange in wireless networks with network coding and physical-layer broadcast," in *Proc. of Conf. on Information Sciences and Systems (CISS)*, Baltimore, MD, USA, March 2005.

[4] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," in *IEEE J. Sel. Areas on Comm.,* vol. 32, no. 9, pp. 1637–1652, Sept. 2014.

[5] T. Riihonen, S. Werner, R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays", in *IEEE Trans. on Signal Processing*, vol. 59, no. 12, Dec. 2011.

[6] J. S. Lemos, F. Rosário, F. A. Monteiro, J. Xavier, A. Rodrigues, "Massive MIMO full-duplex relaying with optimal power allocation for independent multipairs", in *Proc. of 16th IEEE Inter. Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2015)*, Stockholm, Sweden, June 2015.

[7] J. S. Lemos, F. A. Monteiro, I. Sousa, A. Rodrigues, "Full-duplex relaying in MIMO-OFDM frequency-selective channels with optimal adaptive filtering", *accepted for publication in the 2015 IEEE Global Conf. on Signal and Information Processing (Global SIP)*, Orlando, USA, December 2015. Available: http://arxiv.org/abs/1505.00850.

[8] Namyoon Lee, Jong-Bu Lim, Joohwan Chun, "Degrees of freedom of the MIMO Y channel: signal space alignment for network coding", in *IEEE Trans. on Information Theory*, Vol. 56, No. 7, July 2010.

[9] F. S. Bras, F. E. Ferreira, F. A. Monteiro, A. Rodrigues, "Interference suppression with physical-layer network coding and MIMO for multi-way channels," in *2014 IEEE Workshop on Signal Processing Systems (SiPS)*, Belfast, UK, Oct. 2014.

[10] S. Tedik and G. Kurt, "Practical full-duplex physical layer network coding", in *Proc. of IEEE 79th Vehicular Technology Conf. (VTC Spring)*, Seoul, Korea, May 2014.

[11] F. A. Monteiro, I. Wassell, N. Souto, "MIMO detection methods", in *MIMO Processing for 4G and Beyond: Fundamentals and Evolution*, M. Marques da Silva and F. A. Monteiro, Eds. Boca Raton, FL, USA: CRC Press. 2014, ch. 2.