Cooperative Protocol for Analog Network Coding in Distributed Wireless Networks

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***Abstract*—The concept of analog network coding (ANC) considers the concurrent transmission of signals over the wireless medium so that they intentionally interfere. Higher network throughput can be achieved with ANC when an intended transmission that a receiver desires to receive is made to interfere with a concurrent transmission of a signal known a priori at the receiver. In this paper, we present a cooperative protocol that exploits ANC. We consider a system with cooperative relaying of overlapped transmissions from two independent users. More specifically, we explore the case that network nodes may allow the transmitted signals to interfere both at the final destination node, and also at an intermediate node that acts subsequently as a relay. The relay employs a cooperative and multicast amplify-and-forward protocol so that the two destinations can use the interfered signals in order to recover the desired packet. We analyze this protocol in terms of the achieved rate and present an algorithm to recover signals from the overlapped transmissions. We study the impact of overlapping in signal transmissions on the throughput of the system. We show that even with considerable overlapping, the throughput under the proposed protocol is better in comparison to an orthogonal amplify-and-forward protocol.**

***Index Terms*—Wireless networks, cooperative systems, interference cancelation, analog network coding.**

I. Introduction

INTERFERENCE in wireless communication systems has always been considered to be harmful [1]. Wireless networks have thus been designed to prevent transmissions from interfering among each other. A basic idea that prevents interference is to ensure that transmissions take place on orthogonal channels. This can be accomplished with mechanisms like frequency division multiple access (FDMA), time division multiple access (TDMA), or the use of random access protocols like carrier sense multiple access (CSMA) [1]. The utilization of the wireless channel can also be improved by the secondary usage of licensed spectrum where unlicensed devices listen on the channel and transmit only when found idle from licensed devices [2]. Even in such an advanced *cognitive radio* approach, the idea is to avoid causing harmful interference.

The focus of this paper is to exploit concurrent signal transmissions constructively in wireless networks. More specifically we are interested in extending the idea of analog network coding (ANC). ANC is essentially a form of linear self-interference cancelation with the use of a-priori known information. To the best of our knowledge, it was reported first in [3], while in more recent years the idea has evolved in different forms [4]–[10].

Contrary to ANC, when the network coding idea is employed in its digital form, routers algebraically mix the content of the received packets and then transmit the result [11]–[13]. With wireless digital network coding a router that receives packets linearly codes them together over $GF(2)$, and then broadcasts a single packet. ANC takes the same philosophy to the next level - nodes are allowed to transmit packets simultaneously (thus allowing interference) while the corresponding analog signals are mixed naturally over the wireless channel[1] without additional processing at the router. The fundamental assumption that makes ANC effective is that nodes allow their signals to interfere only with known signals, i.e. a-priori information that has been obtained in the past. This scenario is the case in multi-hop networks where the same packet is being forwarded between successive nodes [14].

Although the main principle of concurrent packet transmissions with network coding were established in the works we mentioned earlier, open questions remain regarding how such mechanisms can be generalized in order to increase the achievable throughput in wireless networks. Our work focuses on extending the concept of ANC in two directions. We consider: (1) a network topology and a traffic pattern that is characterized by independent unicast transmissions from two users, and (2) uncoordinated partially interfered packets.

To motivate the first issue, we consider the topology depicted in Fig. 1. In this topology, nodes s_A and s_B intend to transmit packets A and B to nodes d_A and d_B respectively, while R is a random node that would not normally participate in any packet transmission phase. Even with the baseline analog network coding protocols [7], [10], [15], node R in the middle is not the *next hop digital router*. However, the role of R is crucial since it has to determine whether it should relay or not interfering packets. Furthermore, neither of the nodes s_A and s_B have information about each other's impending transmission. The only help that node R can provide is to relay these two transmissions in different time slots in order to achieve diversity gains from cooperation [16], [17]. But in this paper an arbitrary node R is allowed to receive the two independent transmissions concurrently. One question that has to be answered is what is the level of interference that can be allowed at the relay. To motivate the second issue,

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[1]The term "network coding" for the remaining of the paper refers to the analog mixing/overlapping and not to algebraic network coding.

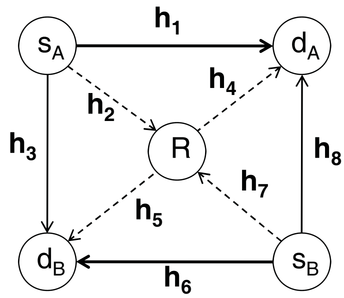

Fig. 1. Analog network coding of independent signal transmissions with the help of a random relay. The packet transmissions are received intentionally (thick solid lines) and unintentionally (narrow solid lines) at the destinations. Signal reception and forwarding at the relay is indicated with dashed lines.

consider again the example in Fig. 1. If the two senders do not reside within each others carrier sensing range, it is impossible for them to know when s_A will transmit to d_A and when s_B will transmit to d_B (hidden terminal problem). The proposed cooperative scheme intends to relax this assumption so that it considers the case of two nodes that transmit packets in a completely uncoordinated fashion while the resulting transmissions may interfere partially over the medium.

From the above issues that we briefly discussed, we can see that our idea is aimed at generalizing networking coding in the analog domain. We consider arbitrary nodes that are not simple routers/destinations as in the digital domain, but they are forwarders (R in Fig. 1) and destinations (d_A, d_B in Fig. 1) of partially interfered signals. From the above simple example we can also already see that the benefit of ANC with relaying might be much broader and in scenarios that ANC did not originally targeted.

The rest of the paper is organized as follows. First, in Section II we provide an analysis of the proposed cooperative analog network coding protocol. A signal recovery algorithm is then presented, followed by an analysis of the achieved rate under the proposed protocol. Aspects of the cooperative protocol are elaborated upon in Section III. Section IV presents simulation results comparing the proposed protocol with an orthogonal amplify-and-forward protocol. In Section V we presented an overview of the related works. Section VI presents conclusions and provides possible directions for future work.

II. System Description and Signal Analysis

In this section, we describe the signal transmissions under the proposed protocol. We shall assume that all nodes depicted in Fig. 1 are within communication range of each other except the two senders s_A and s_B (hidden terminals). The channel transfer functions are denoted by h with suitable subscripts as shown in Fig. 1, so that they include effects such as attenuation, multipath, and Doppler shift [1]. We also denote $\gamma_i = |h_i|^2$. We assume additive white Gaussian noise (AWGN), with zero mean and variance σ^2, and Rayleigh block fading channels where the attenuation is considered constant throughout the transmission of a single frame. For the block-fading channel, the attenuation is considered to be a Rayleigh variable with a mean square value of 1, and different frames are assumed to be subject to different and independent attenuation.

A. ANC with Overlapped Transmissions (ANC-OT) Protocol

According to our scenario, there are two senders that desire to transmit packets A and B, assumed to be of equal length, which we refer to from now on as signals x_A and x_B respectively, in order to make clear that processing of these signals is done in the analog domain. The transmitted signals are received by the intended receivers d_A and d_B and also by R. The purpose of our analysis is to identify whether this overlapped transmission both at the relay and each destination can be allowed and to what extent it can improve the performance.

The cooperative protocol is in two phases, with each of these phases divided into three subphases, as depicted in Fig. 2, for convenience of signal analysis. In the receiving phase, the uncoordinated transmissions from s_A and s_B are heard by R, d_A and d_B. The three subphases correspond to: duration over which non-interfered transmission from s_A is received, duration over which interfered transmissions from s_A and s_B are received and duration over which non-interfered transmission from s_B is received. We assume that a fraction c of each of the signal transmissions is received without overlap at the relay and the destinations.

Corresponding to these signal transmissions, we may write the received signals at R in the three subphases as

$$\begin{aligned} y_R^{(1)} &= \sqrt{P} h_2 x_A^{(1)} + n_R^{(1)}, && (1)\\ y_R^{(2)} &= \sqrt{P} h_2 x_A^{(2)} + \sqrt{P} h_7 x_B^{(2)} + n_R^{(2)}, && (2)\\ y_R^{(3)} &= \sqrt{P} h_7 x_B^{(3)} + n_R^{(3)}, && (3) \end{aligned}$$

where P is the transmission power at s_A and s_B, and $n_R^{(i)}$ denotes AWGN in subphase i. We use superscripts on x_A and x_B to clarify transmissions in different subphases. Similarly, the received signals at d_A in the three subphases of the receiving phase can be written as

$$\begin{aligned} y_{d_A}^{(1)} &= \sqrt{P} h_1 x_A^{(1)} + n_{d_A}^{(1)}, && (4)\\ y_{d_A}^{(2)} &= \sqrt{P} h_1 x_A^{(2)} + \sqrt{P} h_8 x_B^{(2)} + n_{d_A}^{(2)}, && (5)\\ y_{d_A}^{(3)} &= \sqrt{P} h_8 x_B^{(3)} + n_{d_A}^{(3)}. && (6) \end{aligned}$$

Since the signal analysis at node d_B is similar, we shall only consider node d_A in our analysis. In the forwarding phase, R multicasts the three signals (1-3) in three subphases by applying gains g_1, g_2 and g_3 so as to maintain the power constraint [16] in each subphase. The gains are given as

$$\begin{aligned} g_1 &= \sqrt{\frac{P}{\gamma_2 P + \sigma^2}}, \quad g_3 = \sqrt{\frac{P}{\gamma_7 P + \sigma^2}},\\ g_2 &= \sqrt{\frac{P}{(\gamma_2 + \gamma_7) P + \sigma^2}}. \qquad (7) \end{aligned}$$

In the first two subphases of the forwarding phase (fourth and fifth overall), the received signals at d_A can now be written

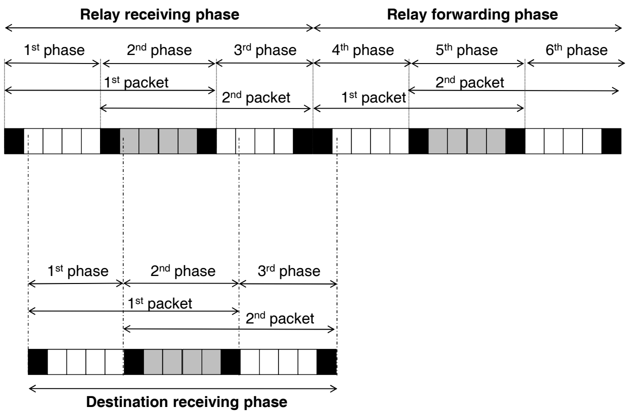

Fig. 2. Timing diagram of the 6-phase relaying used in the analysis. The grey-shaded areas indicate the portions of the packets (in terms of symbols) that are overlapped. The black-shaded areas indicate packet preambles and postambles that are used for channel estimation. Temporal difference in the received signals at the destination and the relay is also depicted.

as

$$\begin{aligned} y_{d_A,R}^{(4)} &= h_4 g_1 y_R^{(1)} + n_{d_A,R}^{(4)} \\ &= \sqrt{P} h_2 h_4 g_1 x_A^{(1)} + h_4 g_1 n_R^{(1)} + n_{d_A,R}^{(4)}, \quad (8) \\ y_{d_A,R}^{(5)} &= h_4 g_2 y_R^{(2)} + n_{d_A,R}^{(5)} \\ &= \sqrt{P} h_2 h_4 g_2 x_A^{(2)} + \sqrt{P} h_4 h_7 g_2 x_B^{(2)} \\ &\quad + h_4 g_2 n_R^{(2)} + n_{d_A,R}^{(5)}. \quad (9) \end{aligned}$$

Note that the signal received in the third subphase of the forwarding phase (sixth overall), which is the non-interfered portion of x_B, is not of interest to d_A. On the other hand, the transmissions in fifth and sixth subphases are of interest to node d_B.

B. Orthogonal Amplify-and-Forward (OAF) Protocol

We shall compare the performance of the ANC-OT protocol with an OAF protocol. We now briefly review the basic elements of the OAF protocol, which is a simple extension of the AF protocol [16] for our topology. The OAF protocol involves transmission in four orthogonal phases, where in the first two phases s_A transmits its data to destination d_A with the assistance of the R and in the next two phases s_B transmits its data to destination d_B with the assistance of the R. Let us consider the two phases that exist in the OAF protocol for node d_A. The signal transmissions for the first and second phases can be respectively written as

$$\begin{aligned} z_R &= \sqrt{P} h_2 x_A + n_R, \quad (10) \\ z_{d_A} &= \sqrt{P} h_1 x_A + n_{d_A}, \quad (11) \end{aligned}$$

$$\begin{aligned} z_{d_A,R} &= h_4 g_1 z_R + n_{d_A,R} \\ &= \sqrt{P} h_2 h_4 g_1 x_A + h_4 g_1 n_R + n_{d_A,R}. \quad (12) \end{aligned}$$

The signal transmissions from s_B to d_B via R take a similar form.

C. Combining and Signal Recovery Algorithm for ANC-OT

We now describe the signal recovery procedure at the destination nodes. First consider the recovery process at destination node d_A. Part of the signal, $x_A^{(1)}$, is recovered using received signals (4) and (8) from the first and fourth subphases corresponding to the receiving and forwarding phase transmissions. Let $\mathcal{X}_\mathcal{A}$ be a fixed symbol dictionary that depends on the modulation scheme used by source s_A. An ML-based decoding is performed as follows to obtain an estimate $\tilde{x}_A^{(1)}$, given by

$$\begin{aligned} \tilde{x}_A^{(1)} &= \arg \min_{x_A^{(1)} \in \mathcal{X}_\mathcal{A}} \{ \| y_{d_A}^{(1)} - \sqrt{P} h_1 x_A^{(1)} \|^2 + \| y_{d_A,R}^{(4)} \\ &- \sqrt{P} h_2 h_4 g_1 x_A^{(1)} \|^2 \}. \quad (13) \end{aligned}$$

The same idea is used at destination d_B to recover part $x_B^{(3)}$ but in this case the last subphases of the transmissions are used. Note that we have implicitly assumed here that d_A has knowledge of the non-interfered portion, i.e. it knows c. The problem of estimating c will be discussed in the following section.

The next step is to retrieve $x_A^{(2)}$ from the interfered portions. For this, we use a joint ML decoding method. Let $\mathcal{X}_\mathcal{B}$ be a fixed symbol dictionary that depends on the modulation scheme employed by s_B. The recovery algorithm takes the form

$$\begin{aligned} (\tilde{x}_A^{(2)}, \tilde{x}_B^{(2)}) &= \arg \min_{(x_A^{(2)}, x_B^{(2)}) \in \mathcal{X}_\mathcal{A} \times \mathcal{X}_\mathcal{B}} \Big\{ \| y_{d_A}^{(2)} - \sqrt{P} h_1 x_A^{(2)} \\ &- \sqrt{P} h_8 x_B^{(2)} \|^2 + \| y_{d_A,R}^{(5)} - \sqrt{P} h_2 h_4 g_2 x_A^{(2)} \\ &- \sqrt{P} h_4 h_7 g_2 x_B^{(2)} \|^2 \Big\}. \quad (14) \end{aligned}$$

Note that if ANC was not employed, the component $x_B^{(2)}$ would be pure interference that would degrade or make completely impossible the recovery of $x_A^{(2)}$. Note also that the recovery steps (13) and (14) require channel knowledge. This can be obtained via the use of training symbols that are inserted in the preamble and postamble of each packet [15].

D. Rate Analysis

Having described the signal recovery algorithms and the relaying protocol, we proceed with the derivation of the theoretical rate of our system.

For the OAF protocol, the rate is given by

$$R_{OAF} = \frac{R_{OAF,A} + R_{OAF,B}}{4}, \quad (15)$$

where

$$\begin{aligned} R_{OAF,A} &= \log_2 \left(1 + \frac{P\gamma_1}{\sigma^2} + \frac{P\gamma_2\gamma_4 g_1^2}{g_1^2 \gamma_4 \sigma^2 + \sigma^2} \right) \\ R_{OAF,B} &= \log_2 \left(1 + \frac{P\gamma_6}{\sigma^2} + \frac{P\gamma_5\gamma_7 g_3^2}{g_3^2 \gamma_5 \sigma^2 + \sigma^2} \right). \quad (16) \end{aligned}$$

The rate R_{ANC-OT} for the ANC-OT protocol may be written as

$$R_{ANC-OT} = \frac{cR_{AF,A} + cR_{AF,B} + (1-c)R_{ANC}}{2(1+c)}, \quad (17)$$

where $R_{AF,A}$ and $R_{AF,B}$ are the rates corresponding to non-overlapped parts of the transmission for users s_A and s_B respectively, while R_{ANC} is the total rate for the overlapped interfered portions at both receivers d_A and d_B. The reason why this term is included only once is explained below, while later the value for R_{ANC} is calculated at both receivers ($R_{ANC,A}$ and $R_{ANC,B}$). The term $R_{ANC,A}$ that we calculate in the next paragraph corresponds to the total rate at d_A from the decoding not only of the symbols in the signal $x_A^{(2)}$, but also of the symbols $x_B^{(2)}$ that originated from the second sender s_B. While the symbols in $x_B^{(2)}$ are "useless" for the rate calculation at d_A, we include them as part of the total rate of the system which of course includes the rate after decoding these symbols at node d_B. This approach of calculating the total rate with (17) is possible since assume a symmetric network *only for this part of our work and for simplifying the rate calculation*. The result of the assumption at this stage is that $R_{ANC,A} \simeq R_{ANC,B} \simeq R_{ANC}$. The proposed protocol and the associated decoding algorithm are completely agnostic to the symmetry of the network since channel estimation is performed on the fly based on the preambles. In case we desire an expression for an asymmetric network, the formulations of $R_{ANC,A}$ and $R_{ANC,B}$ that we provide below are still valid. However, in that case (17) is more complicated and we should subtract from it the rate from decoding "useless" symbols as we defined them above for each destination. The final note regarding (17) is that the term in the denominator $2(1+c)$ is the duration of the overall ANC-OT transmission, with c the overlap given in terms of number of symbols. For example, for completely overlapped signals, c is equal to 0 which means that two transmission slots are needed in total. On the other hand, when $c = 1$, we have the case of OAF and (17) reduces to the rate expressions (15-16).

To proceed with the derivation of each term in (17), let us first calculate $R_{AF,A}$. To do this, we consider the non-overlapped signal transmissions received at d_A given by (4) and (8) and write them in matrix form

$$\tilde{\mathbf{Y}}_{d_A}^{(1)} = \tilde{\mathbf{H}}_A^{(1)} x_A^{(1)} + \tilde{\mathbf{N}}_A^{(1)}, \qquad (18)$$

where $\tilde{\mathbf{Y}}_{d_A}^{(1)} = [y_{d_A}^{(1)}, y_{d_A,R}^{(4)}]^T$, $\tilde{\mathbf{H}}_A^{(1)} = [\sqrt{P}h_1, \sqrt{P}h_2h_4g_1]^T$, and $\tilde{\mathbf{N}}_A^{(1)} = [n_{d_A}^{(1)}, h_4g_1n_R^{(1)} + n_{d_A,R}^{(4)}]^T$. Now performing pre-whitening, we obtain

$$\hat{\mathbf{Y}}_{d_A}^{(1)} = \hat{\mathbf{H}}_A^{(1)} x_A^{(1)} + \hat{\mathbf{N}}_A^{(1)}, \qquad (19)$$

where $\hat{\mathbf{Y}}_{d_A}^{(1)} = [y_{d_A}^{(1)}/\sqrt{\sigma^2}, y_{d_A,R}^{(4)}/\sqrt{\lambda_1}]^T$, $\hat{\mathbf{H}}_A^{(1)} = [\sqrt{P}h_1/\sqrt{\sigma^2}, \sqrt{P}h_2h_4g_1/\sqrt{\lambda_1}]^T$, $\hat{\mathbf{N}}_A^{(1)} = [n_{d_A}^{(1)}/\sqrt{\sigma^2}, (h_4g_1n_R^{(1)} + n_{d_A,R}^{(4)})/\sqrt{\lambda_1}]^T$, and $\lambda_1 = \sigma^2(1 + \gamma_4 g_1^2)$. Note that $E[\hat{\mathbf{N}}_A^{(1)}\hat{\mathbf{N}}_A^{(1)\dagger}|\hat{\mathbf{H}}_A^{(1)}] = I$. The achievable rate $R_{AF,A}$ is then given by

$$\begin{aligned} R_{AF,A} &= \log_2 \det\left(I + \hat{\mathbf{H}}_A^{(1)}\hat{\mathbf{H}}_A^{(1)\dagger}\right) \\ &= \log_2\left(1 + \frac{P\gamma_1}{\sigma^2} + \frac{P\gamma_2\gamma_4 g_1^2}{\lambda_1}\right). \end{aligned} \qquad (20)$$

The expression for $R_{AF,B}$ can be similarly computed.

Now let us consider the derivation of $R_{ANC,A}$. For this, consider the overlapped signal transmissions received at d_A given by (5) and (9) written in matrix form as

$$\tilde{\mathbf{Y}}_{d_A}^{(2)} = \tilde{\mathbf{H}}_A^{(2)}\tilde{\mathbf{X}} + \tilde{\mathbf{N}}_A^{(2)}, \qquad (21)$$

where $\tilde{\mathbf{Y}}_{d_A}^{(2)} = [y_{d_A}^{(2)}, y_{d_A,R}^{(5)}]^T$, $\tilde{\mathbf{H}}_A^{(2)} = \begin{bmatrix} \sqrt{P}h_1 & \sqrt{P}h_8 \\ \sqrt{P}h_2h_4g_2 & \sqrt{P}h_4h_7g_2 \end{bmatrix}$, $\tilde{\mathbf{X}} = [x_A^{(2)}, x_B^{(2)}]^T$, and $\tilde{\mathbf{N}}_A^{(2)} = [n_{d_A}^{(2)}, h_4g_2n_R^{(2)} + n_{d_A,R}^{(5)}]^T$. Pre-whitening along the lines described earlier, we obtain the whitened channel matrix $\hat{\mathbf{H}}_A^{(2)} = \begin{bmatrix} \sqrt{P}h_1/\sqrt{\sigma^2} & \sqrt{P}h_8/\sqrt{\sigma^2} \\ \sqrt{P}h_2h_4g_2/\sqrt{\lambda_1} & \sqrt{P}h_4h_7g_2/\sqrt{\lambda_1} \end{bmatrix}$. Thereupon, we have

$$\begin{aligned} R_{ANC,A} &= \log_2 \det\left(I + \hat{\mathbf{H}}_A^{(2)}\hat{\mathbf{H}}_A^{(2)\dagger}\right) \\ &= \log_2\Bigg(1 + \frac{P\gamma_1}{\sigma^2} + \frac{P\gamma_8}{\sigma^2} + \frac{P\gamma_2\gamma_4 g_2^2}{\lambda_1} \\ &\quad + \frac{P\gamma_4\gamma_7 g_2^2}{\lambda_1} + \frac{P^2\gamma_1\gamma_4\gamma_7 g_2^2}{\sigma^2\lambda_1} + \frac{P^2\gamma_2\gamma_4\gamma_8 g_2^2}{\sigma^2\lambda_1} \\ &\quad - \frac{P^2\gamma_4 Re(h_1h_2^*h_7h_8^*)g_2^2}{\sigma^2\lambda_1}\Bigg). \end{aligned} \qquad (22)$$

Similarly we derive the expression for $R_{ANC,B}$.

III. Protocol for Cooperative Relaying of Collided Signals

The previous section provided the basic analysis that supported our adaptive signal recovery algorithm. In this section, we propose further elements of the protocol in more detail that make use of the aforementioned algorithm.

A. Packet Overlap Estimation

An essential feature of the protocol is that both the relay and the destination nodes monitor the signal to be relayed and calculate the number of symbols that are received without interference. In our case, the correlation of the received signals with the known preambles is calculated in order to identify the start of a packet. In this way, a node can identify the start of a packet that interferes with another ongoing transmission. From that indication it estimates the number of non-overlapped symbols c, which is easy to derive for a constant packet length. Fig. 4 presents visually this aspect. Detecting the start of the interfering packets can also be done by measuring the variance of the received signal energy at least for MSK modulation as described in [15].

As we showed in Fig. 2, the level of overlap may be different at the relay and the destinations. Regardless of this difference, both the relay and the destinations need to perform channel estimation from the inserted preambles and postambles of the two collided packets that are received. The relay needs to calculate c in order to apply AF adaptively, i.e. enforce different power constraints on the overlapped and non-overlapped portions of the signal as we showed in our analysis. On the other hand, each destination estimates c in order to decode jointly the correct symbols. This is needed at the destination so that it can decide whether to perform ML demodulation for the overlapped part of the signal (14),

$process\_pkt\_dst\_d_A()$

Store partially overlapped direct signal y_{d_A}
Store partially overlapped forwarded signal $y_{d_A,R}$
for all symbols until end of packets **do**
  Calculate $correlation(y_{d_A}, preamble)$
  Calculate $correlation(y_{d_A,R}, preamble)$
  Estimate c
  Estimate channels h_1, h_2h_4, h_8, h_4h_7
  if uninterfered signal **then**
    Estimate $\tilde{x}_A^{(1)}$ with ML detection (13)
  else if interfered signal **then**
    Estimate $\tilde{x}_A^{(2)}, \tilde{x}_B^{(2)}$ with ML detection (14)
  end if
end for

$process\_pkt\_relay\_R()$

Store partially overlapped signal
Estimate channel
for all symbols until end of packet **do**
  Calculate $correlation(y_R, preamble)$
  Estimate c'
  Apply power control according to (7)
end for

Fig. 3. Pseudo-algorithm for the relaying protocol at node d_A and the relay R.

or for the non-interfered portion (13). An important aspect of our system is that each destination performs independently the correlation operation for the directly received packet and the forwarded packet. This is necessary since different portions of the packets may be overlapped at the relay and at the destination.

B. Packet Forwarding

Another task of the relay is to AF packets without attempting to decode the received signals. With this protocol, the relay always executes AF on the interfered signals depending on its power constraints. Therefore, besides the correlation operation the computational overhead is minimal at the physical layer of the relay. Although it is out of the scope of this paper, there is a need for a mechanism at the relay that ensures that two packets that randomly collide will only be forwarded if the same signals have also collided at the destinations. This operation requires network layer information in order to identify such topologies. A signaling protocol that identifies opportunities for algebraic wireless network coding by exploiting overheard packets was presented in [13] and its main principle can also be applied here.

Finally, we should note that the sender does not discard the packet from the transmission queue unless it receives an acknowledgment from the destination. Possible re-transmissions of the packet are handled again with regular unicast transmission from the sender at the link layer. This is another advantage of the proposed protocol since it does not compromise and or break the functionality of higher layer protocols.

IV. Simulation Results

We implemented the proposed system and we evaluated the performance in terms of BER and throughput under different

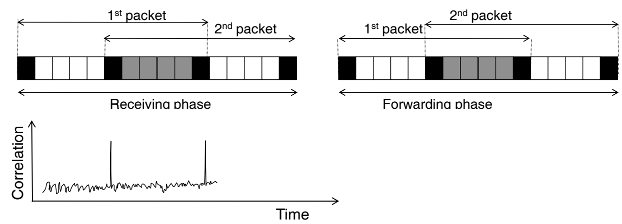

Fig. 4. Interfered/collided packets at the receivers and the relay visualized in terms of symbols. Correlation with the preamble spikes in the middle of the packet.

conditions. We assume a channel bandwidth of W=22 MHz, while the same path loss model was used for all the channels. We calculate the BER for 10,000 packet transmissions. The distances between the nodes are all set symmetrically at a distance equal to one unit, while we also assumed the same transmit power for the two senders. For presenting our simulations we named our scheme ANC-OT in all these figures. For comparing our protocols, we also implemented a typical relaying scheme named OAF, that employs orthogonal transmissions between each sender but also orthogonal relaying phases from the relay [16]. Therefore, in the later case signals did not interfere with each other. We also evaluated the performance of direct orthogonal transmissions without a relay and this scheme was named Direct. Preambles and postambles of 32 bits were used for channel estimation. We assumed that these preambles and postambles were not overlapped even the case of fully overlapped transmissions in order to perform the necessary channel estimation. Furthermore, we also assume that the noise over the wireless spectrum is additive white Gaussian noise (AWGN) with the variance of the noise to be 10^{-9} W/Hz at every node/link. We also used a Rayleigh fading wireless channel model. Our assumptions in this case include a frequency-flat fading wireless link that remains invariant per transmitted PHY frame, but may vary between simulated frames. For slow-varying flat fading channels, the channel quality can be captured by the average received SNR γ of the wireless link. Since the channel varies from frame to frame, the Nakagami-η fading model is adopted for describing γ. This means that the received SNR per frame is a random variable, where we assume $\eta = 1$ for Rayleigh fading.

A. Performance for Different Percentage of Overlap

The most interesting part is to evaluate the performance of the full-fledged protocol that is able to exploit different level of interference at the receiver. We experimented with the level of signal overlap/interference in the time domain. The related results for the BER can be seen in Fig. 5(a) for different level of signal overlap and a fully symmetric network. For comparing the proposed protocols with the classical orthogonal cooperative relaying, we use the throughput as a metric because naturally non-interfered transmissions will have lower BER. Nevertheless, the proposed ML detector for the interfered signals can reduce the BER considerably even with overlap which means that one can expect significant throughput benefits. The related normalized throughput results

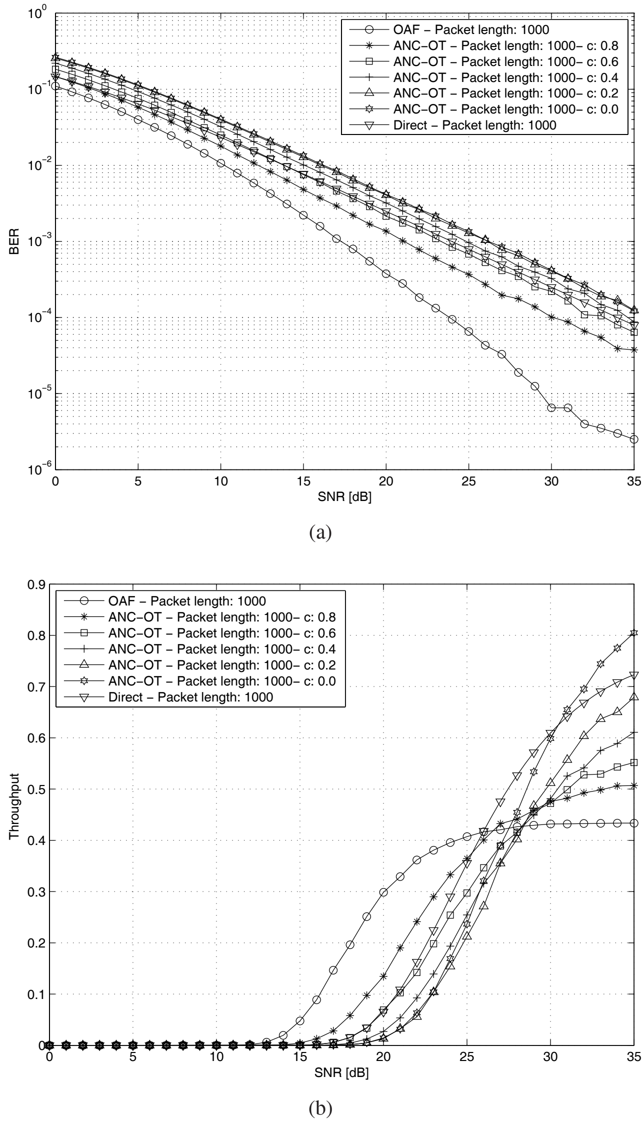

Fig. 5. BER and throughput results for a BPSK modulation scheme. Packet length 1000 bits.

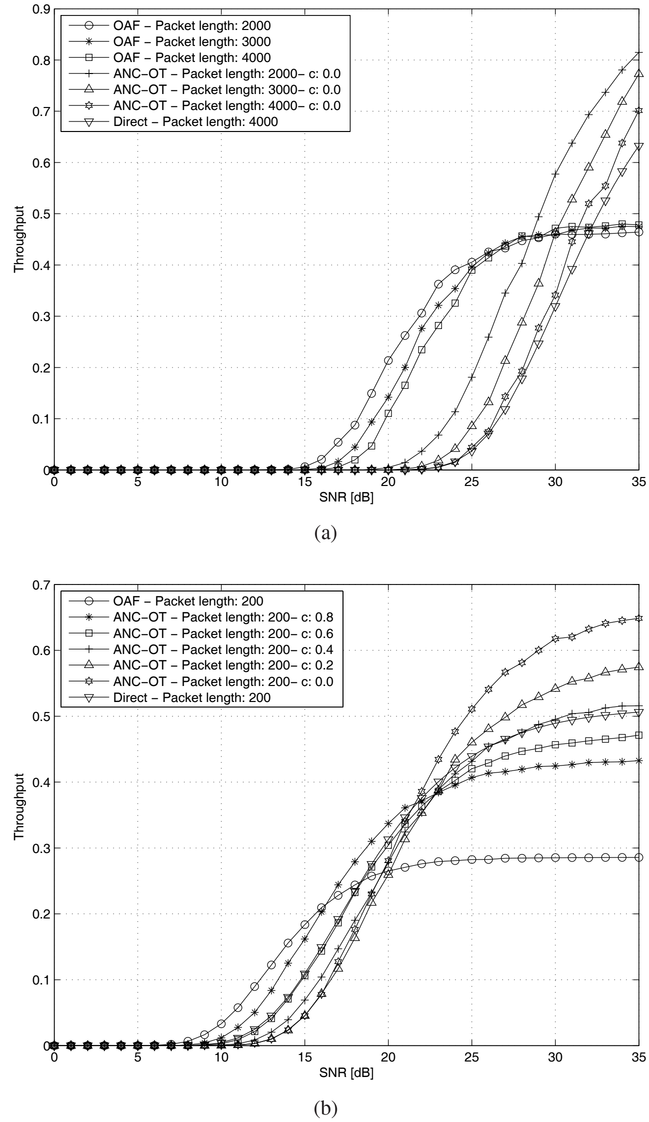

Fig. 6. Throughput results for a BPSK modulation scheme and different packet lengths (a) and different level of overlap (b).

can be seen in Fig. 5(b) for a packet length of 1000 bits. In this figure, OAF means that the relay executes AF by using orthogonal transmissions that are not overlapped at all, while with Direct the two senders transmit orthogonally without the help of a relay. The general observation from these results is that the throughput is superior with ANC-OT under good channel conditions and it is also improved as the percentage of packet overlap is increased. For example when the channel conditions are poor, in order for the proposed ANC-OT to achieve performance closer to OAF, a reduced overlap should be enforced in the received signals (or otherwise a higher c). But as the channel quality improves, the throughput is increased with any ANC-OT scheme which means that the system can allow a higher percentage of overlap and achieve higher throughput gains. It is also important to see the performance of the Direct scheme that outperforms the ANC-OT protocol for a specific SNR range. Note also that for the selected packet length in this simulation set, fully overlapped transmissions is the most efficient scheme over all the others when the SNR improves. We investigate more this issue in our next experiment.

B. Performance for Different Packet Lengths

Next, we evaluated the performance of the two systems under test for different packet length and for the same network setup with before. In this case we considered packets that consisted of 2000, 3000, and 4000 bits and we present these results in Fig. 6(a). Note in this figure that for an increased packet length the achieved rate of the proposed ANC-OT system requires better channel conditions but the performance of the OAF scheme is affected to a lesser degree. In Fig. 6(b) we present the results for a smaller packet length of 200 bits and different level of overlap. In this case we see actually that there is another level of overlap namely $c = 0.8$ under which the ANC-OT scheme is optimal for a specific SNR regime. As with before, with improved channel conditions, the full overlap is again the optimal choice. Note also the performance of the Direct scheme that performs worse from the majority of

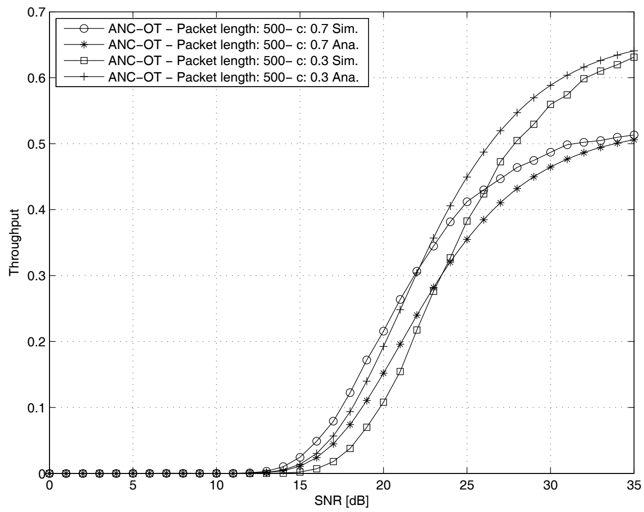

Fig. 7. Comparison between simulation and analytical results.

schemes that use ANC-OT. Therefore, we can see that the full overlap is the best choice when channel conditions improve while partial overlap can also be beneficial if a complete overlap cannot be achieved from higher layer protocols. Our scheme is flexible and enables any of these choices to be used. Our conclusion from this set of experiments is that as the packet length decreases ANC-OT becomes the most efficient choice for packet transmission.

C. Analytical Model Validation

Our simulation results provided a detailed look into the performance improvement that can be achieved with our system. The final step is to evaluate whether the obtained simulation results can be compared with the analytical rate expressions we developed. We believe that this is a very important step since a simple closed-form rate expression could potentially be used for driving decisions at the relay with a more advanced cooperative protocol. For simplifying the analytical expression in (22), we assume that $h_1 \approxeq h_8$ and $h_2 \approxeq h_7$. This assumption simplifies (22) and it means that a closed form result can be obtained for this part of our evaluation.

Comparative simulation and analytical results for the system throughput can be seen in Fig. 7. We present results for a specific packet length of 500 bits and c equal to 0.4 and 0.7 respectively. These results indicate that the analytical rate expression approximates the performance that we obtain from a simulated system. The good match is due to the fact that our analytical model takes into account the impact of the secondary interfering transmissions. Similar results were also obtained for different payloads.

V. Related Works

Early on, techniques on the receiver side that took interference into consideration for increasing the capacity of wireless networks were based on multi-user detection (MUD). MUD techniques specifically focused on disentangling interfering signal transmissions [18], [19]. These techniques have been applied so as to allow the concurrent signal transmissions while MAC protocols have also been developed [20]. For example, MUD with cooperative relaying has been investigated in [21]. Also Huang *et al.* [22] employed the idea for CDMA systems. In that work the authors considered a scenario where each relay may cooperate with multiple users simultaneously. Messages received from multiple sources are decoded using a multi-user detector at the relays and are jointly processed before being forwarded sequentially to the base station.

A smarter exploitation of interference is accomplished with superposition coding. Superposition coding was first proposed by Bergmans and Cover in [23] and it was studied more recently in [24]–[26]. The work presented by Katti *et al.* in [15] is a form of superposition coding for a topology similar to the one in Fig. 1. However, in that work the proposed system attempts to decode independently the overheard and relayed version of the superimposed signals leading to higher number of packet failures. More recently Zhang *et al.* presented algorithms for optimizing the recovery of superimposed signals for an extended set of digital modulation schemes [27]. Our work is considerably different from [15] in the sense that we employ a joint decoding algorithm for improving the symbol decoding probability, while it is independent of the modulation scheme [27].

Another class of works investigated more intelligent roles for the relays. Larsson *et al.* proposed a scheme where the relay has a central role and encodes data packets after reception [4], [5]. This technique is similar to digital network coding. An approach that considered the idea of ANC with packets that have been transmitted in the past by a network node was presented by Popovski and Yomo in [6], [7]. Another type of work that considered sophisticated relaying techniques is by Boppana and Shea that proposed the overlapped CSMA protocol [14]. The main task of the relay in that work is to estimate the level of secondary interfering transmissions that another primary transmission can sustain. Also Zhang *et al.* [28] proposed a similar idea. More recently, Katti *et al.* presented the MIXIT scheme where wireless network nodes decode a subset of the symbols that belong to a packet [29]. Subsequently relays forward mixed symbols and not complete packets.

One characteristic of all the previous works is that they assume that nodes have transmitted in the past the signal that is used for removing interference. In our work we considered completely independent unicast transmissions with no a-priori knowledge of specific signals.

VI. Conclusions

In this paper, we introduced a cooperative protocol that leverages interfering packet transmissions from two different physical locations in a wireless network. With the proposed protocol a relay node forwards the locally interfered version of the two packets to the intended destinations. At the destination a decoding algorithm uses the local and forwarded versions of the interfered signals to recover the desired packet. Simulation results showed significant throughput gains of the proposed protocol for different levels of packet overlap. In the future, we plan to investigate the problem of relay selection in an extended multi-hop wireless local area network.

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