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Cooperative Protocol for Analog Network Coding in Wireless Networks

Antonios Argyriou
Department of Electrical and Computer Engineering
University of Thessaly, Greece

Ashish Pandharipande
Distributed Sensor Systems
Philips Research, The Netherlands

***Abstract*—We consider a cooperative protocol for wireless networks employing analog network coding (ANC) for the case of independent, uncoordinated transmissions. In particular, we present a protocol under which network nodes allow the transmitted signals to interfere both at the final destination of the signal and also at an intermediate node that subsequently acts as a relay of the interfered signal. The relay employs cooperative and multicast amplify-and-forwarding. We analyze this cooperative protocol and present an algorithm to recover signals from overlapped transmissions. We study the impact of overlapped signal transmissions on the throughput of the system, and show that even under considerable interference, the performance of the system is improved in comparison to an orthogonal amplify-and-forward protocol.**

I. Introduction

A changing paradigm in wireless networks is to exploit interference, rather than avoid it. Towards this end, transmission protocols using analog or physical layer network coding [7], [14] have recently been considered. Here, general network coding concepts that have nodes combine packets in a network besides simply forwarding them were introduced. In ANC, nodes are allowed to transmit packets simultaneously, thus allowing for interference to occur, while the corresponding analog signals are mixed naturally over the wireless channel without additional processing at the routing nodes. The fundamental assumption that makes ANC effective is that nodes allow their signals to interfere only with known signals that they have transmitted in the past. This scenario is the case in multi-hop networks where the same packets are being forwarded between successive nodes [2]. This simple observation facilitates interference cancelation in the mixed packets since the signal that needs to be removed is perfectly known.

Nevertheless, the topic of concurrent wireless signal transmission based on ANC and opportunistic listening to transmissions is relatively new. While one body of work [1], [2], [7]- [9], [13]- [15] has focused on using ANC for improving network throughput, another body of work [3]- [6], has exploited overheard signal transmissions for improving spectrum utilization with cognitive radios. In ANC with opportunistic listening [7], intermediate nodes listen to interfering transmissions and forward these analog signals. Destination nodes use prior knowledge of interference to recover the desired transmission after canceling out the interference component. In [2], an overlapped CSMA protocol was introduced in order to improve spatial reuse in wireless multi-hop networks. The protocol is based on the distributed coordination function mode in IEEE 802.11 MAC along with extended RTS/CTS handshaking. Concurrent wireless transmissions were studied in [15] from a scheduling viewpoint for WLAN downlink. Signal recovery algorithms for different modulation schemes for time-varying channels were presented in [13]. Cooperative protocols to achieve secondary spectrum access by exploiting knowledge of primary system transmissions were introduced in [4], [5], [6] in the context of spectrum sharing using cognitive radios. In [4], [5], a secondary system node listens to primary signal transmissions and superimposes the secondary signal along with primary signal to gain secondary access while maintaining the QoS of the primary system. The commonality between the two bodies of work discussed here is that overheard transmissions are exploited in some way to improve overall network performance. Our work falls in the first category of works that consider the scenario where nodes forward overheard interfered signals that are used to decode corresponding signals at destination nodes.

In this paper, we investigate ANC for independent transmissions. An example system setup in shown in Fig. 1, where s_A and s_B are two independent sources, with respective destinations d_A and d_B, and relay node R. We shall study a generalization of ANC to deal with uncoordinated, partially overlapped transmissions from s_A and s_B. The cooperative protocol that we study works as follows. In the receiving phase, nodes R, d_A and d_B listen to uncoordinated transmissions from s_A and s_B. In the next forwarding phase, R multicasts the overlapped analog signal it has heard. Nodes d_A and d_B employ decoding based on a maximum-likelihood (ML) criterion to retrieve their respective signals. An important question we shall be addressing in this paper is the impact of overlap in transmissions on the performance of the protocol in comparison to an orthogonal amplify-and-forward (AAF) scheme.

II. Analysis of Cooperative Relaying with interfered Transmissions

In this Section, we describe the signal transmissions under the proposed protocol. We shall assume that all nodes depicted in Fig. 1 are within sensing and communication range of each other. We denote the channel transfer functions by h, with suitable subscripts as shown in Fig. 1, so that it includes effects such as attenuation, multipath, and Doppler shift [12].

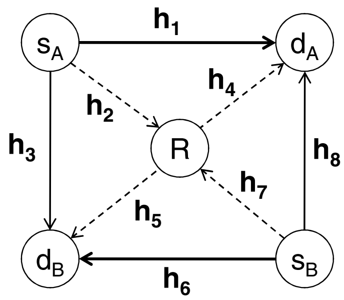


Fig. 1. Analog network coding of independent signal transmissions with the help of a relay. The packet transmissions are received intentionally (thick solid lines) and unintentionally (narrow solid lines) at the destinations. Signal reception and forwarding at the relay is indicated with dashed lines.

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 attenuations.

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. One assumption that we make is that a higher layer protocol has allocated transmission slots to the two senders under consideration [10]. This means that the cooperative and partially overlapped packet transmissions can proceed after some sort of scheduling has been performed. 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

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

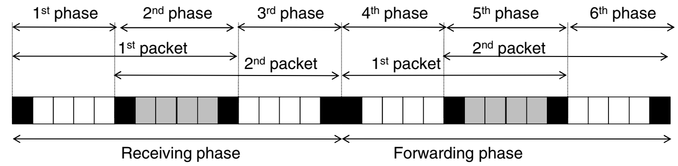


Fig. 2. Timing diagram of the 6-phase relaying used in the analysis. The gray shaded areas indicate the portions of the packets (in terms of symbols) that are overlapped. The black shaded areas indicate packet preambles and postambles that are used for channel estimation.

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 [10] in each subphase. The gains are given as

$$g_1 = \sqrt{\frac{P}{\gamma_2 P + \sigma^2}}, \quad (7)$$

$$g_2 = \sqrt{\frac{P}{(\gamma_2 + \gamma_7) P + \sigma^2}}, \quad (8)$$

$$g_3 = \sqrt{\frac{P}{\gamma_7 P + \sigma^2}}. \quad (9)$$

In the first two subphases of the forwarding phase, the received signals at d_A can now be written as

$$\begin{aligned} y_{d_A,R}^{(1)} &= h_4 g_1 y_R^{(1)} + n_{d_A,R}^{(1)}\\ &= \sqrt{P} h_2 h_4 g_1 x_A^{(1)} + h_4 g_1 n_R^{(1)} + n_{d_A,R}^{(1)}, && (10)\\ y_{d_A,R}^{(2)} &= h_4 g_2 y_R^{(2)} + n_{d_A,R}^{(2)}\\ &= \sqrt{P} h_2 h_4 g_2 x_A^{(2)} + \sqrt{P} h_4 h_7 g_2 x_B^{(2)}\\ &\quad + h_4 g_2 n_R^{(2)} + n_{d_A,R}^{(2)}. && (11) \end{aligned}$$

Note that the signal received in the third subphase, 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.

We now describe the signal recovery procedure at the destination nodes.

A. Signal Recovery Algorithm

We describe the recovery process at destination node d_A. Part of the signal, $x_A^{(1)}$, is recovered using received signals (4) and (10) 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

$$\begin{aligned}\tilde{x}_A^{(1)} &= \arg \min_{x_A^{(1)} \in \mathcal{X}_{\mathcal{A}}} \{\|y_{d_A}^{(1)} - \sqrt{P}h_1 x_A^{(1)}\|^2 \\ &+ \|y_{d_A,R}^{(1)} - \sqrt{P}h_2 h_4 g_1 x_A^{(1)}\|^2\}. \end{aligned} \tag{12}$$

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

$$\begin{aligned}(\tilde{x}_A^{(2)}, \tilde{x}_B^{(2)}) &= \arg \min_{(x_A^{(2)}, x_B^{(2)}) \in \mathcal{X}_{\mathcal{A}} \times \mathcal{X}_{\mathcal{B}}} \{\|y_{d_A}^{(2)} - \sqrt{P}h_1 x_A^{(2)} \\ &- \sqrt{P}h_8 x_B^{(2)}\|^2 + \|y_{d_A,R}^{(2)} - \sqrt{P}h_2 h_4 g_2 x_A^{(2)} \\ &- \sqrt{P}h_4 h_7 g_2 x_B^{(2)}\|^2\}. \end{aligned} \tag{13}$$

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 (12) and (13) require channel knowledge. This can be obtained via the use of training symbols that are inserted in the preamble and postamble of each packet [7].

$symbol\_decode\_destination()$

Store partially overlapped signal
Decode PLCP header
Estimate channel
for all symbols until end of packet **do**
  Calculate $correlation(y_{d_A}, preamble)$
  if uninterfered signal **then**
    Estimate $\tilde{x}_A^{(1)}$ with ML detection (12)
    Store estimated symbols as $x_A^{(1)}$
  else if interfered signal **then**
    Estimate $\tilde{x}_A^{(2)}, \tilde{x}_B^{(2)}$ with ML detection (13)
    Store estimated symbols as $x_A^{(2)}$, $x_B^{(2)}$
  end if
end for

$process\_pkt\_relay()$

Store partially overlapped signal
Decode PLCP header
Estimate channel
for all symbols until end of packet **do**
  Calculate $correlation(y_r, preamble)$
  if un-interfered signal **then**
    Apply power control according to (7) or (9)
  else if interfered signal **then**
    Apply power control according to (8)
  end if
end for

Fig. 3. Pseudo-algorithm for the ANC relaying protocol and the signal recovery algorithm.

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 a protocol that makes use of the aforementioned algorithm.

A. Packet Overlap Estimation

The most essential feature of the protocol is that both the relay and the receivers monitor the signal to be relayed and try to calculate the number of symbols c that are received without interference. In our case, we calculate the correlation of the received signals with the known preambles 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 size. 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 [7].

As we showed in Fig. 2, c 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 (two unknown symbols), or for the un-interfered portion (one unknown symbol). An important aspect is that the destination performs independently the correlation operation for the directly received packet and the forwarded packets. This is necessary since different portions of the packets may be overlapped at the relay and at the destination like Fig. 2 depicts.

B. Packet Forwarding

Another important 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 PHY 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 the potential ”X” topologies. A signaling protocol that identifies opportunities for algebraic wireless network coding by exploiting overheard packets was presented in [1] and its main principle could also be applied in the context of ANC.

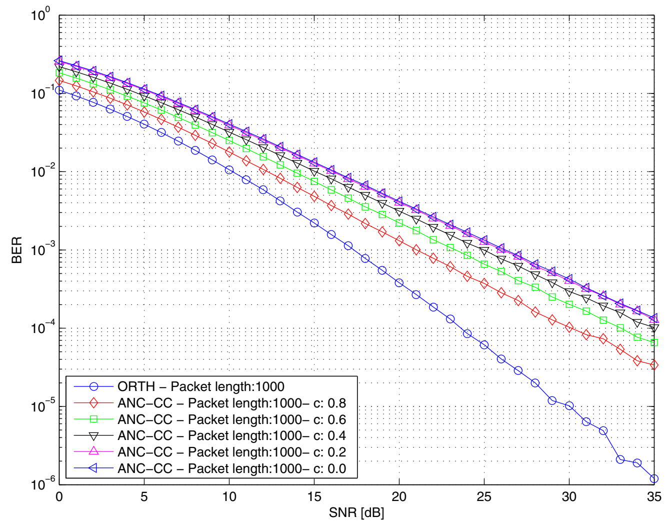
Finally, we should note that the sender does not discard the packet from the transmission queue unless it receives an acknowledgement from the destination. Possible retransmissions of the packet are handled again with regular unicast transmission from the sender at the link layer. This is another advantage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

IV. Simulation Results

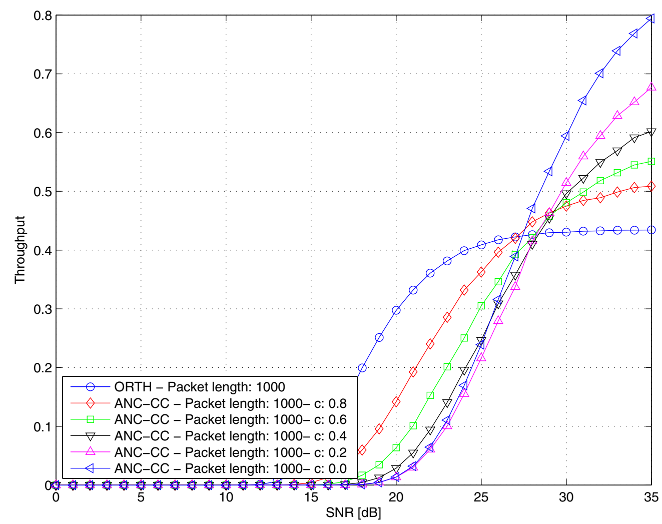
We implemented the proposed protocol and we evaluated the performance in terms of BER and throughput under different parameter settings. We assume a channel bandwidth of $W = 22$ MHz. The distances between the nodes are all set symmetrically at a distance equal to one unit, while the same path loss model was used for all the channels. Simulations were performed over 10,000 packet transmissions. For presenting our simulations we labeled our scheme $ANC-CC$ in all these figures. For comparing our protocol, we also implemented a conventional relaying scheme, labeled $ORTH$, that employs orthogonal transmissions between each sender but also orthogonal relaying phases from the relay [10]. In $ORTH$, transmission from s_A to d_A happens in two phases. In the first phase, s_A transmits to d_A and R. In the next phase, R forwards the overheard signal to d_A. Transmission from s_B to d_B occurs similarly with the aid of R in the next two phase. Therefore, in $ORTH$, transmissions do not interfere with each other. Finally, we used a 32 bit preamble and postamble for channel estimation. Furthermore, we also assume that the noise over the wireless spectrum is AWGN with the variance of the noise to be 10^{-9} at every node. 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 main objective is to evaluate the performance of our protocol that is able to exploit different levels of interference at the destination nodes. The related results for the BER can be seen in Fig. 4(a) for different level of signal overlap. For comparing the proposed protocol with $ORTH$, we use the throughput as a metric because naturally non-interfered transmissions will have lower BER. Results showing throughput for $ANC - CC$ and $ORTH$ are shown in Fig. 4(b) for a packet size of 1000 bits. The general observation from these results is that the throughput is superior with $ANC - CC$ 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 $ANC - CC$ to achieve performance closer to $ORTH$, a reduced overlap should be enforced in the received signals. However as the channel quality improves, the throughput is increased with any $ANC-CC$ scheme which means that the system can afford a higher percentage of overlap and achieve higher throughput gains. Note also that for the selected packet size in this simulation set, fully overlapped transmissions is the most efficient scheme over all the others in the high SNR region.



(a) BER



(b) Normalized system capacity

Fig. 4. BER and Throughput results for a BPSK modulation scheme. Packet size 1000 bits.

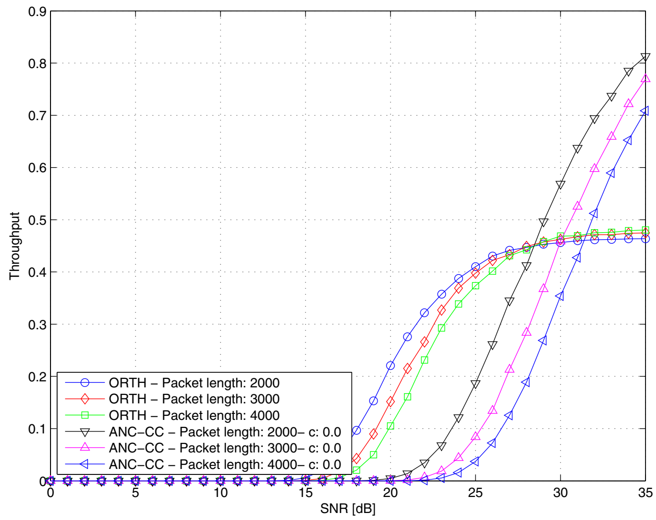


Fig. 5. Throughput comparison for varying packet lengths

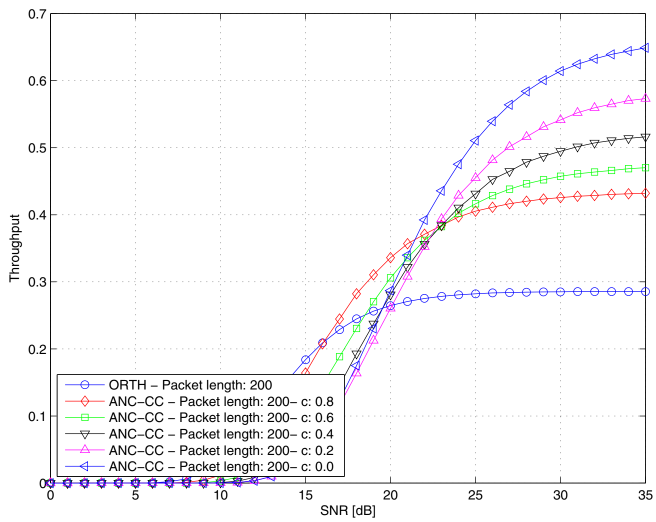


Fig. 6. Throughput comparison for fixed packet length

B. *Performance for Different Packet Sizes*

Next, we evaluated the performance of $ANC-CC$ and $ORTH$ for different packet sizes under the same network setup as before. In this case we considered packets that consisted of 2000, 3000, and 4000 bits and we present these results in Fig. 5. Note in this figure that for an increased packet length the achieved rate of the proposed $ANC-CC$ system requires better channel conditions but the performance of the $ORTH$ scheme is affected to a lesser degree. In Fig. 6 we present the results for a smaller packet size of 200 bits and different level of overlap. In this case we see actually that there is a level of overlap, $c \approx 0.8$, under which the $ANC-CC$ scheme performs better in a specific SNR regime ($\sim$ 17-21 dB) than the other schemes depicted in the figure. As before, with improved channel conditions, full overlap is again the optimal choice. Therefore, we can see that completely overlapped transmissions is the best choice when channel conditions improve while partial overlap can also be beneficial if a complete overlap in transmissions cannot be achieved under higher layer protocols.

V. Conclusions

We analyzed a cooperative protocol for wireless networks that leverages interfering signals over two spatially different locations in the network. When combined with simple ML-based decoding, the proposed approach facilitates successful signal recovery from interfered transmissions. Our simulation results validated the substantial performance gains of the scheme under different percentages of packet overlap. In the future, we will extend our results for relay selection in a wireless network when multiple independent packet flows exist.

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