Collision Recovery in Distributed Wireless Networks with Opportunistic Cooperation

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***Abstract*—In this letter we focus on the problem of recovering information from collided packets in distributed wireless networks that are based on the IEEE 802.11 standard. We propose a cooperative protocol that employs the concept of physical layer network coding for this purpose. With the proposed protocol relay nodes opportunistically forward locally collided packets to the destinations. Subsequently, the destination nodes recover the desired packet by employing a detection algorithm that combines the directly-collided and forwarded-collided signals.**

***Index Terms*—Packet collisions, CSMA/CA, cooperative protocol, physical layer network coding.**

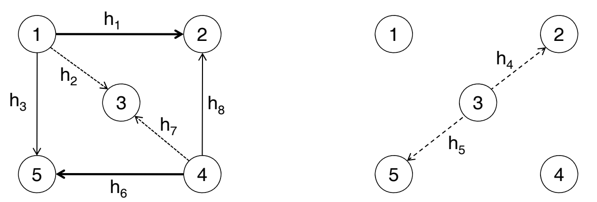

Fig. 1. Topology and signal analysis. Solid thick lines indicate the direct intended transmissions, while solid lines over channels h_3,h_8,h_2,h_7 indicate the overheard packets. The left figure is the collision of two packets in the same time slot. In the right the relay forwards the locally collided packets.

I. Introduction

ONE of the major problems of random multiple access protocols is that the probability of packet collisions is increased as more nodes contend for the medium. In addition, the existence of hidden terminals will also lead to an increased number of collisions. However, several recent works suggest the exploitation of interfering transmissions in order to improve network throughput [1], [2], [3], [4]. This concept is usually referred to as analog or physical layer network coding (PLNC). According to PLNC, nodes store signals that they have transmitted in the past so that interference cancellation can be easily applied to retrieve the signal of interest.

In this letter we extended this concept in order to recover from packets collisions in a distributed IEEE 802.11 wireless network. In IEEE 802.11, once a collision occurs it lasts until the colliding packets have been completely transmitted. In this case the receivers cannot decode the received packets and therefore they cannot send back acknowledgments (ACKs). A transmitter only perceives the success or failure of a packet transmission based on whether an ACK is received or not, but does not know the reason of the packet loss. In this letter we exploit the fact that collisions also take place in more nodes in the network besides the intended receivers of the colliding packets. A third node is allowed to act as a relay and opportunistically forward the collided packets/signals to the two destination nodes. This approach is unlike works that consider collision recovery from re-transmissions of the same packet [5]. The benefit is that collision resolution can take place at any time instant regardless of the time synchronization differences between the two versions of the two collided packets [5]. The proposed relaying protocol and the signal recovery algorithm are presented next.

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II. Proposed System

Our protocol does not affect the channel contention mechanism but only the packet transmission procedure in case of a collision. Basically when a collision happens, network nodes are given one more chance to successfully decode the collided packet by using a relayed signal instead of executing directly the backoff algorithm.

A. Correlation-Based Collision Detection

The first issue that has to be solved is how to identify concurrent packet transmissions that resulted in a collision as Fig. 1 indicates. When a collision takes place, the baseline 802.11 protocol retransmits the data frame after a specific timeout duration [6]. With our protocol, the relay performs a correlation operation between a known preamble and the received signal in order to infer whether two packets have collided [5]. This operation is depicted in Fig. 3. Since it is difficult for an arbitrary relay node to infer whether the two packets have collided at both destinations, an additional delay of a single slot (t_s) is needed after the reception of the collided packets at the relay. More specifically, when the channel is not active after a short inter-frame space (SIFS) plus t_s, the relay infers that a collision took place also at the destinations since there is a lack of transmitted ACKs after $SIFS$ (see Fig. 2).

B. Relaying

Fig. 2 presents the channel access mechanism that includes the modifications to the IEEE 802.11 MAC. With the proposed protocol, a relay that also overhears the concurrent transmission of two data packets from nodes N_1 and N_4 is responsible for forwarding the locally received version of the collided packets. After collision is detected the relay N_3 switches the radio into transmit mode (TX) and after a duration of $SIFS + t_s$ it *amplifies-and-forwards* (AF) the received collided packets that is indicated as DATAR in Fig. 2. At

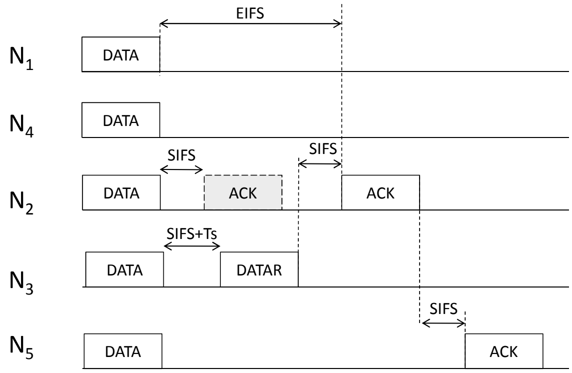

Fig. 2. Timing diagram of the distributed MAC protocol for the topology in Fig. 1. The dark-shaded ACK packet indicates the behavior in a successful direct transmission.

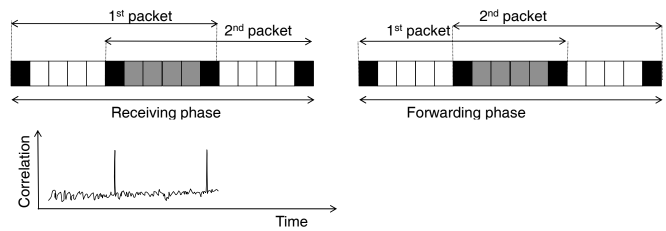

Fig. 3. Collided packets at the receivers and the relay in terms of symbols. Correlation with the preamble spikes when the preambles and postambles of two packets coincide.

the receiver side, both of the receivers N_2 and N_5 have already a collided signal that they are required to store. Note also from Fig. 2 that after a duration of $SIFS + t_s$, the receiving nodes expect the reception of the forwarded-collided signal DATAR. Subsequently, the receivers execute the signal recovery algorithm, recover the desired packet and send ACK after $SIFS$. The difference in this case is that the sender can receive an ACK at two different time instants that they are both valid: Either after $SIFS$ or after $2SIFS+t_s+T_{DATA}$, i.e. either successful direct or relayed transmissions. This is the only timing implication that has to be accounted at the sender. If a frame is not acknowledged during these two time slots, then the node executes normally the backoff procedure.

C. Timeout Duration

In IEEE 802.11 [6], the extended inter-frame space ($EIFS$) is used when the physical layer has indicated to the MAC that a frame transmission started but that frame transmission did not result in the correct reception of a complete MAC frame with a correct FCS (Frame Check Sequence) value. According to the IEEE 802.11 standard the duration of the $EIFS$ is equal to $SIFS+DIFS+[8ACK_{size}+Preamble\_length+PLCPHeaderLength]/BitRate$. Therefore, the $EIFS$ interval begins following indication by the physical layer that the channel is idle after sensing of the erroneous frame. In our case the duration of the $EIFS$ is extended by $SIFS+t_s+T_{DATA}$. This means that $EIFS$ is not constant but depends on the duration of the data packet. However, this duration is known to the sender which means that in practice there is no problem in calculating it. Note that with the proposed protocol, the advantage is that the receivers do not need to explicitly identify which packets collided since they know implicitly that signals will be forwarded after the regular collided packet transmission. Also, there is no requirement that the mixed signals are perfectly synchronized.

In this letter we assume that a random relay is selected for serving throughout the session, although more sophisticated relay selection strategies could also be used [7].

D. ACK Prioritization

The impact of relaying the same packet to more than one receivers is that if the original data packets are decoded at both destination nodes, both of them will need to ACK their respective packet. To address this problem we allow the nodes to prioritize the ACKs as follows. The minor time delay between the originally collided packets is also taken into consideration by the receivers for this purpose. As Fig. 3 indicates this can also be induced from the forwarded and collided packet. The first node that decodes successfully a data packet sends the ACK after $SIFS$. In practice, after the relayed packet is received and decoded successfully, the receiving node switches to TX mode and transmits the ACK. To prevent collision between ACKs, the relay marks with an arbitrary order the forwarded packet with the node ids. In this way the second node knows that it should wait for $SIFS+T_{ACK}+SIFS$ before the transmission of an ACK.

E. Recovery of Collided Packets/Signals

The next important question is how to process the received signals at the destinations given that interfered signals are received during two distinct phases, namely during the direct and during the forwarding phases. *To this aim we apply standard symbol detection algorithms, but in this case it is executed for symbols that belong to different packets*. More specifically, the main idea of our scheme is to use maximum ratio combining (MRC) together with maximum-likelihood (ML) demodulation after the second receiving phase which besides allowing us to estimate packet x_A, it allows the receiver to estimate packet x_B. Let $\mathcal{X_A}, \mathcal{X_B}$ be a fixed symbol dictionary that depends on the modulation scheme that the two senders use. Let the channel gains be denoted as h with the appropriate subscripts and the power allocation factor at the relay as g. If combining of direct and relayed signals is employed at node N_2 with a single ML demodulation step, the estimation will take the form

$$\begin{aligned}(\tilde{x}_A,\tilde{x}_B)_{N_2} = \arg &\min_{x_A\in\mathcal{X_A},x_B\in\mathcal{X_B}} \{\|y_{N_2} - \sqrt{P_{N_1}}h_1x_A \\ &-\sqrt{P_{N_4}}h_8x_B\| + \|y_{N_3,N_2} - \sqrt{P_{N_1}}h_2h_4gx_A \\ &-\sqrt{P_{N_4}}h_4h_7gx_B\|\}. \qquad (1)\end{aligned}$$

At the second receiver, a similar formula can be written.

The parameters $\sqrt{P_{N_4}}h_4gh_7, \sqrt{P_{N_1}}h_4gh_2$ are obtained by using the training symbols that are inserted in the preamble and postamble of each packet [8]. Fig. 3 depicts how this is accomplished. Related works like [3], leverage the asynchronous reception of packets at the relay and the receivers in order to use the preambles for channel estimation.

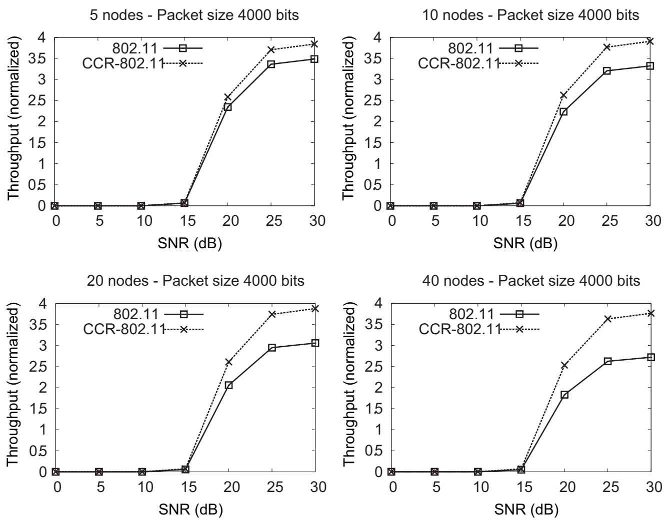

Fig. 4. Simulation results for a packet size of 4000 bits.

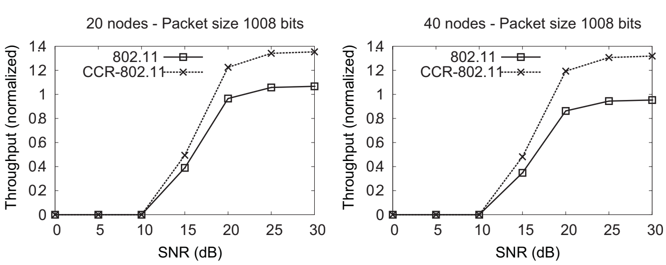

Fig. 5. Simulation results for a packet size of 1000 bits.

III. Performance Evaluation

We assume that nodes reside in the single cell and that pairs of nodes want to communicate to each other. For relay selection we use a simple metric based on the average number of successfully relayed/received packets. We implemented the proposed system and we evaluated the performance in terms of BER and throughput under different SNR regimes. 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, while we also assumed the same transmit power for all senders. For presenting our simulations we named our scheme cooperative collision recovery (CCR) in all these figures. 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} 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 [8]. This means that the received SNR per frame is a random variable, where we assume $\eta = 1$ for Rayleigh fading.

In Fig. 4 we present results for different number of nodes and for different conditions of the wireless channel with a packet size of 4000 bits. The later parameter is important to be evaluated since it affects the performance of the ML detection operation that is executed at the receivers. The results are very important and they show that for a higher number of nodes the aggregate MAC layer throughput can stay very high. Therefore, the impact of high collision rate for a higher number of nodes is mitigated by the proposed CCR algorithm. It is important to note that with the proposed protocol the performance is lower bounded always by the baseline 802.11 MAC since a collision is always a wasted opportunity for the baseline protocol. For example even for channel conditions with low SNR, the performance of ML detection is naturally lower but in this case even with the baseline 802.11 the performance is low (regardless of collisions) only because of the higher BER. Therefore, our scheme works well and in pace with IEEE 802.11.

Results for a packet size of 1000 bits can be seen in Fig. 5. The results are consistent with our previous results although the total performance of the system is lower because of the smaller packet size. However, the percentile performance difference between the proposed scheme and the baseline 802.11 is higher and starts to increase already from the lowest values of the SNR regime. Therefore, our scheme is more essential for traffic with smaller packet sizes.

IV. Conclusions

In this letter we proposed an cooperative collision recovery protocol that can be used in distributed wireless networks for recovering from collisions. The protocol can recover essentially from two-packet collisions that probabilistically dominate in distributed wireless networks. The throughput increase that was observed was more important for lower packet sizes due to the improved performance of the ML detection algorithm.

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