

Cooperative Retransmissions Through Collisions

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Abstract—Interference in wireless networks is one of the key capacity-limiting factors. Recently developed interference-embracing techniques show promising performance on turning collisions into useful transmissions. However, the interference-embracing techniques are hard to apply in practical applications due to their strict requirements. In this paper, we consider utilising the interference-embracing techniques in a common scenario of two interfering sender-receiver pairs. By employing opportunistic listening and analog network coding (ANC), we show that compared to traditional ARQ retransmission, a higher retransmission throughput can be achieved by allowing two interfering senders to cooperatively retransmit selected lost packets at the same time. This simultaneous retransmission is facilitated by a simple handshaking procedure without introducing additional overhead. Simulation results demonstrate the superior performance of the proposed cooperative retransmission.

I. INTRODUCTION

Compared with centralized *medium access control* (MAC) protocols, random access based MAC protocols such as *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) do not suffer from single point of failure and the network scalability problem, and thus it has become dominant in *wireless local area networks* (WLANs). However, using random access for multiple nodes to share a common channel inevitably introduces collisions or interferences, especially at heavy traffic load.

Numerous approaches have been proposed to deal with wireless signal interference. The common idea is to avoid collision as much as possible. For example, CSMA/CA uses carrier sensing and random backoff to avoid collision. Other techniques [1] include channel assignment, load balancing and power control. All these techniques can alleviate wireless interference to a certain extent, but cannot completely eliminate interference.

In 2006, Zhang *et al.* [2] introduced a novel idea of decoding a transmission collision on a wireless channel, which directly challenges the traditional rule, that a collided transmission on a wireless channel is undecodable. In this pioneering work called *physical-layer network coding* (PNC) [2], it shows that two simultaneous wireless transmissions added together at the electromagnetic wave level can be decoded to produce an outcome same as network coding. Katti *et al.* [3] further elaborated this concept of embracing wireless interference and proposed an *analog network coding* (ANC) scheme, which is more practical than PNC.

Despite this remarkable idea of turning collisions into useful transmissions, it is hard to apply PNC and ANC in practical

applications. There are a few reasons for that. First, PNC and ANC are only suitable for decoding a superimposed transmission consisting only of two simultaneous transmissions. Second, the collided transmissions need to be well synchronized, although a perfect synchronization is not required for ANC. Third, in order to decode a superimposed transmission, one of the two collided transmissions needs to be known. All these constraints limit the use of the interference-embracing techniques.

Although so far there is no practical solution to decode a superimposition of multiple (more than two) transmissions, some recently developed schemes [4], [5] show that it is possible to tell the presence of individual transmissions involved in a collision. These techniques have been successfully applied to improve the reliability of wireless broadcasting [4], [5]. The idea is that upon receiving a broadcast transmission, each receiver detecting the transmission replies with an *acknowledge* (ACK) transmission. These simultaneous ACK packets transmissions cause a collision. Then, decoding of the superimposed ACK packet is performed to identify the ACK transmitters. The synchronization issue is well handled in this case since simultaneous ACK transmissions appear after the completion of a broadcast transmission which is a common event.

In this paper, we consider utilizing the interference-embracing techniques in a common unit of two interfering sender-receiver pairs. Particularly, we study the scenario of two interfering WLAN APs, which are simulcasting bulky data to their associated individual stations in a lossy environment as shown in Fig. 1. This scenario is in line with the increasing density of WLAN APs and the increasing popularity of multimedia applications such as video streaming and online games [1], [6]. Due to the high performance to price ratio, more and more WLANs are being deployed in public and residential places. Thus, it is quite common that multiple APs overlap with each other and share a common channel, especially in metropolitan cities.

By employing opportunistic listening and ANC, we show that compared to traditional ARQ retransmission, a higher retransmission throughput can be achieved by allowing two interfering APs to cooperatively retransmit selected lost packets at the same time. This simultaneous retransmission is facilitated by a simple handshaking procedure without introducing additional overhead. Simulation results demonstrate the superior performance of the proposed cooperative retransmission.

The rest of the paper is organized as follows. Section II

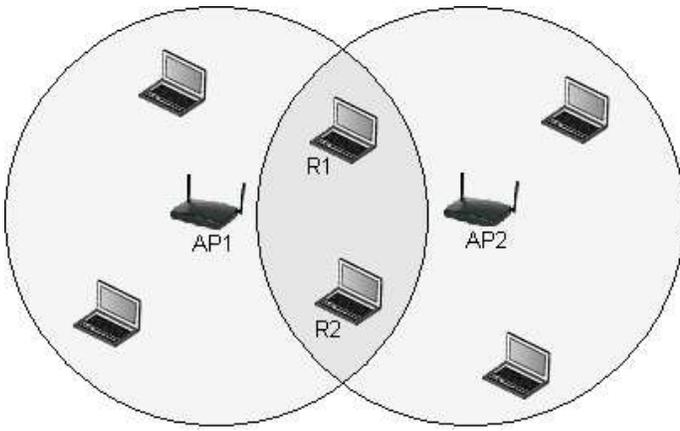


Fig. 1. Two interfering APs.

reviews the existing interference-embracing techniques. Section III introduces our ideas and describes the detailed protocol design. We analyze the proposed collision based retransmission scheme in Section IV and provides the simulation results in Section V. Finally, we conclude the paper in Section VI.

II. RELATED WORK

In this section, we review the existing interference-embracing techniques, including interference based network coding and superimposed acknowledgement. These techniques will be incorporated into our proposed scheme as individual components.

A. Interference Based Network Coding

The idea of turning a collision of two simultaneous wireless transmissions into a useful transmission was first introduced in PNC [2]. In particular, the authors proposed a frame-based decode-and-forward strategy in packet forwarding. In their scenario of a relay network, two nodes transmit simultaneously to a common receiver. Assuming perfect transmission synchronization at the physical layer, based on the additive nature of simultaneously arriving *electromagnetic waves* (EM), the receiver detects a single collided signal which is the sum of the two transmitted signals. Using a suitable mapping scheme, they show that for certain modulation schemes, there exists a mapping scheme such that the relationship between the two transmitted binary bits and the decoded binary bit follows the *exclusive-or* (XOR) principle.

ANC [3] was further proposed to relax the restrictions of symbol-level synchronization, carrier-frequency synchronization and carrier-phase synchronization required in PNC, which makes ANC more practical. Specifically, ANC is able to decode an unknown packet c_2 from a collided packet $c_1 \odot c_2$ ¹ based on the known packet c_1 by leveraging the co-channel FM signal separation technique [7] and network layer information to cancel the interference.

¹ We use the notation \odot to denote a collision of two packet transmissions.

B. Superimposed Acknowledgement

As mentioned, some interesting methods [4], [5] have been proposed to decode superimposed ACKs for providing reliability in wireless multicast, where the requirement is not to decode the content of the collided packets but to detect the existence of individual ACKs from different receivers. In [5], Durvy *et al.* proposed to use a bit sequence of $N + 1$ bits to decode a collision of up to N simultaneous ACK transmissions. The main limitation of the scheme is that it requires precise power level differentiation in the decoding procedure. Comparisons of analog received signals are needed for the operation, and a delay line is used to store analog signals for the comparison purpose.

In our previous work [4], we design a coding method, called collision codes, used in the MAC layer that can also achieve the decoding of the collided ACK transmissions. Our coding method does not require precise detection of signal energy and thus there is no modification needed for the physical-layer modulation. In particular, each receiver assigns a unique bitstream pattern to embed in its ACK packet. Different superimpositions of these bitstream patterns result in different decoded bitstream, which enables the sender to deduce the presence of individual ACK transmissions involved in the collision. In this way, there is no need for each receiver to transmit its ACK in different time slots.

III. PROPOSED COOPERATIVE RETRANSMISSIONS THROUGH COLLISIONS

In this section, we will show how these interference-embracing techniques can be used in a common scenario of two interfering pairs of sender-receiver communicating in a lossy environment. We will use the case of two interfering WLAN APs as an example to illustrate our idea, although it can be applied to other wireless network scenarios as well.

A. Basic Idea

Consider the two pairs, $AP_1 \sim R_1$ and $AP_2 \sim R_2$ in Fig. 1, in a lossy wireless network, where both receivers are within the transmission range of the two APs. Let us assume that AP_1 wishes to transmit a packet c_1 to R_1 and AP_2 wishes to transmit a packet c_2 to R_2 . Suppose that after the transmission packet c_1 is not heard by R_1 but overheard by R_2 , while packet c_2 is not heard by R_2 but overheard by R_1 due to the broadcast nature of wireless transmission (also known as opportunistic listening [3]). In this case, rather than retransmitting each of the two lost packets in different time slots to avoid interference, it is possible that both AP_1 and AP_2 retransmit their packet c_1 and c_2 simultaneously, which can be decoded by the two receivers using ANC as each of them already has one known packet. In this way, we can improve the retransmission efficiency by reducing one retransmission.

B. Protocol Design

In the practical scenario of two interfering APs shown in Fig. 1, there are typically multiple receivers associated with

each AP. For receivers located in non-interference regions, their transmission and retransmission follow the standard IEEE 802.11 protocol. Only for receivers located in the interference region, the retransmission is carried out using both the proposed cooperative collision and the conventional ARQ.

In order to enjoy the proposed cooperative retransmission, two receivers belonging to different APs in the interference region need to be paired up. In particular, each receiver station first connects to an AP. After the establishment of the $AP_i \sim R_i$ connection, the receiver then detects whether it is in the interference region by overhearing transmission from another AP, AP_j . If it is in the interference region, it then broadcasts its availability to pair-up with receiver R_j connected to AP_j and located inside the interference region. If receiver R_j is available, it accepts the pairing invitation. After that, both R_i and R_j broadcast their pairing information to the APs. Once paired, both R_i and R_j can acknowledge packets destined for anyone of them and no third receiver is allowed to participate in acknowledging packets destined for either R_i or R_j .

Suppose we have established the connections of $AP_1 \sim R_1$ and $AP_2 \sim R_2$ and the pair-up of $R_1 \sim R_2$ as shown in Fig. 1. Initially, both APs will transmit and retransmit packets using 802.11 MAC protocol and both receivers will reply with an ACK embedded with the collision codes [4] for every packet they hear and destined to anyone of them. If both receivers hear the same packet, they will transmit their ACKs simultaneously and the APs use the aforementioned technique [4] to decode the superimposed ACK. If AP_1 only detects an ACK from R_2 for a packet c_1 destined for R_1 , it defers the retransmission until it finds an opportunity for cooperative retransmission. Because of the broadcasting nature of ACK transmission, AP_2 is aware that AP_1 has deferred a retransmission. When AP_2 only detects an ACK from R_1 for a packet c_2 destined for R_2 , AP_2 is then available to participate in cooperative retransmission. Since both APs are aware of each other's deferred retransmission status, they then simultaneously retransmit their corresponding packets, which results in a collision. Once the receivers successfully decode the collided packet using ANC, they will send superimposed ACK immediately. Figure 2 illustrates the handshake procedure for the cooperative retransmission.

IV. PERFORMANCE ANALYSIS

So far, we only show that there is a possibility that the interference-embracing techniques can be utilized to improve the retransmission efficiency in the scenario of two interfering sender-receiver pairs. In this section, we mathematically analyze the probability and corresponding performance gain.

A. System Model

Let d_{AP} denote the distance between the two APs, and r_t denote the transmission range of each AP with both APs transmitting at the same transmission power and the same transmission rate. Consider that the interfering APs are overlapped such that $d_{AP} < 2r_t$. Each AP associates with N client stations, which are uniformly distributed within the

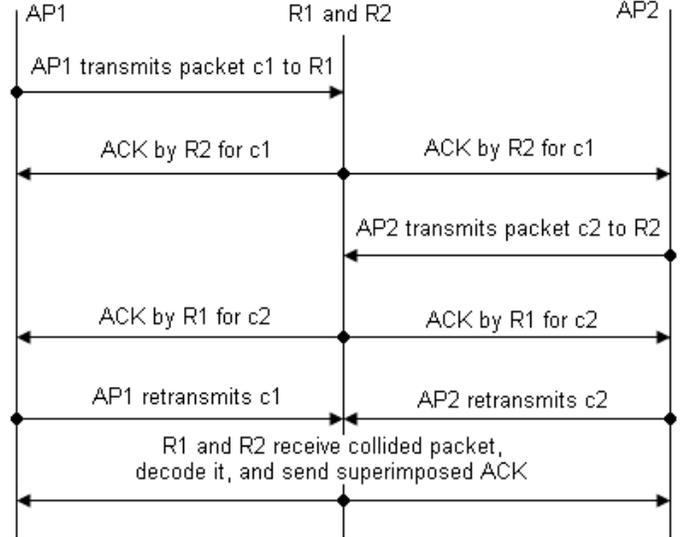


Fig. 2. Example of the handshake procedure for cooperative retransmission.

TABLE I
PACKET RECEPTION STATUS FOR A PACKET TRANSMITTED BY AP_i .

| State | Definition | Probability |
|-------|--------------------------------------|----------------------------|
| 1 | received by R_i but not by R_j | $p_{ij}(1 - p_{ii})$ |
| 2 | received by R_j but not by R_i | $p_{ii}(1 - p_{ij})$ |
| 3 | received by both R_i and R_j | $(1 - p_{ii})(1 - p_{ij})$ |
| 4 | not received by both R_i and R_j | $p_{ii}p_{ij}$ |

transmission range of the AP. Of interest to us are the receivers located inside the interference region. Consider the two pairs $AP_1 \sim R_1$ and $AP_2 \sim R_2$ shown in Fig. 1. Average packet loss probability p_{ij} for transmissions from AP_i to receiver R_j follows an independent Bernoulli packet loss model [8], where $\{i, j\} \in \{1, 2\}$. Packet batch size for transmissions from AP_i to R_i is denoted as B_i . We assume that $B_1=B_2=B$. For multimedia applications such as video streaming, B is usually a large value.

B. Retransmission Efficiency

We use ARQ as the benchmark for performance comparison. It is well known that the average number of retransmissions needed for recovering a lost packet follows the geometric distribution. Thus, the average total number of retransmissions needed for both AP_1 and AP_2 to successfully deliver B packets is

$$N_{ARQ} = \sum_{i=1}^2 \frac{B \cdot p_{ii}}{(1 - p_{ii})}. \quad (1)$$

In our proposed scheme, each AP builds up packet reception status for every packet it transmits. Because of the broadcasting nature of superimposed ACK, AP_i is aware of the reception status of both R_i and R_j . Therefore, any transmitted packet will have four reception states shown in Table I.

Since the packets transmitted by AP_i is destined to R_i , both state 1 and state 3 in Table I are considered instances of

TABLE II
PACKET RECEPTION STATES OF COOPERATIVE RETRANSMISSION AT R_i .

| State | Definition | Probability |
|-------|--------------------------------------|--------------------------------|
| S_a | successfully receive $c_1 \odot c_2$ | $(1 - p_{ii})(1 - p_{ji})$ |
| S_b | $c_1 \odot c_2$ is corrupted. | $1 - (1 - p_{ii})(1 - p_{ji})$ |

successful reception cases. For state 4, where the packet is not received by both receivers, AP_i would repeatedly retransmit the packet in traditional ARQ fashion until the retransmission falls into any one of the first 3 states. The total number of retransmissions needed for changing the packet reception status for all packets in state 4 to one of the first 3 states follows geometric distribution with average loss probability of $p_{i1}p_{i2}$. Thus, the total number of retransmissions needed for packets in state 4 by both the senders is calculated as

$$N_{CR-S4} = \sum_{i=1}^2 \frac{B \cdot p_{i1}p_{i2}}{1 - p_{i1}p_{i2}}. \quad (2)$$

State 2 in Table I is the case for cooperative retransmission. Suppose AP_1 and AP_2 are now simultaneously retransmitting c_1 and c_2 to R_1 and R_2 , respectively. There are two states for the reception of $c_1 \odot c_2$ at each receiver, as shown in Table II. Note that only when both c_1 and c_2 reach R_i successfully, the reception of the collided packet at R_i is considered as a success. This is because any corruption in one of the packets will cause the collided packet undecodable by using ANC.

Therefore, the total number of retransmissions needed for state 2 can be derived as

$$N_{CR-S2} = \frac{B \cdot P_{S2,i}}{(1 - p_{ii})(1 - p_{ji})} \quad (3)$$

where $P_{S2,i}$, the probability that a transmitted packet by AP_i is in state 2, is given by

$$P_{S2,i} = p_{ii}(1 - p_{ij}) \left\{ 1 + \sum_{n=1}^{\infty} (p_{ii}p_{ij})^n \right\}, \quad (4)$$

which takes into consideration additional packets falling in state 2 after retransmission of packets in state 4. Note that unlike (1) and (2), there is no summation sign in (3). This is because of the collision based cooperative retransmission, where the retransmissions for one receiver can always be piggyback in the retransmissions for another receiver.

It is reasonable to assume that both AP_1 and AP_2 can always find ‘partner packets’ in cooperative retransmission for multimedia applications such as video streaming, which typically have large B values. In practice, if there is no ‘partner packets’, those lost packets are just retransmitted in the traditional way.

Finally, we compute the total number of retransmissions needed for our proposed cooperative retransmission as

$$N_{CR} = N_{CR-S4} + N_{CR-S2}. \quad (5)$$

Assuming that $p_{11} = p_{12} = p_{21} = p_{22} = p$, we derive the retransmission gain against ARQ as

$$G_r = \frac{N_{ARQ}}{N_{CR}} = \frac{2(1 - p^2)}{2p(1 - p) + 1}, \quad (6)$$

which gives a theoretical retransmission gain of $2 > G_r > 1$ for $0 < p < 1/2$.

We now derive the total gain for the entire network, where each AP is associated with N uniformly distributed receivers. According to the system model in Section IV-A and the geometry relationships shown in Fig. 1, we can derive the overlapped area as

$$A = 2r_t^2 \left(\arccos \frac{d_{AP}}{2r_t} \right) - d_{AP} \sqrt{r_t^2 - \frac{d_{AP}^2}{4}}. \quad (7)$$

It is clear that the total network gain depends on the number of receiver pairs located in the overlapped area, which is $N_A = N \cdot \frac{A}{\pi r_t^2}$. Therefore, the total retransmission gain with respect to all receivers in the network is given as

$$G_N = \frac{N \cdot N_{ARQ}}{N_A \cdot N_{CR} + (N - N_A) \cdot N_{ARQ}}. \quad (8)$$

V. SIMULATION RESULTS

Packet decoding using ANC has been successfully demonstrated on a test bed in [3]. Therefore we can confidently assume that ANC is a practically applicable technique. For the proposed collision based cooperative retransmission, we construct a C++ discrete-time simulator with the system model described in Section IV-A. For simplicity, we assume the network environment for the two APs are homogeneous and symmetric, e.g. same packet loss rate and distance between $AP_1 \sim R_1$ and $AP_2 \sim R_2$.

Fig. 3 shows the retransmission gain G_r under different packet loss probabilities. We can see that the simulation results with $B = 1000$ matches the theoretical results well. The relatively large difference at low packet loss rates is due to the unavailability of ‘partner packet’ for the cooperative retransmission.

Compared with the results with $B = 1000$ and $B = 100$, we can see that the difference between the theoretical gain and the simulation gain becomes smaller with the increase of the batch size. This is because a larger batch size leads to more cooperative collision coding opportunities, which is consistent with the assumptions we made in the theoretical analysis. On the other hand, for the case of small batch size, the problem of no ‘partner packet’ becomes more severe.

It can also be seen from Fig. 3 that the retransmission gain is reduced with the increase of packet loss rate. There are two main reasons for this. First, large packet loss rate reduces the probability of successful reception of the collided packets as shown in Table II. Second, with the increase of packet loss rate, the probability for state 4 becomes significant (see Fig. 4), where the traditional ARQ based retransmission is used, and thus it reduces the gain from the cooperative retransmission.

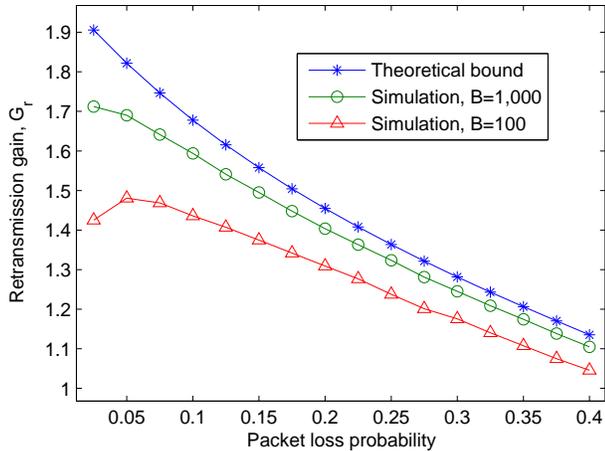


Fig. 3. Retransmission Gain G_r under different packet loss rates.

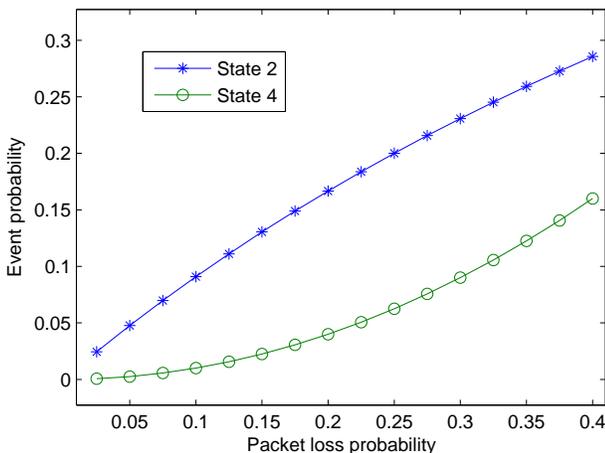


Fig. 4. Probabilities of state 2 and state 4.

Fig. 5 shows the network retransmission gain as the overlap area increases, for which the distance between the APs decreases. Each AP is associated with 10 uniformly distributed receivers. With the increase of the overlapped area, more receivers are located inside the overlapped region, where there are more pairs for the cooperative retransmission. As expected, from Fig. 5, we can see that the network gain increases with the increased number of receivers located in the overlapped area.

VI. CONCLUSION

In this paper, we have successfully applied the existing interference-embracing techniques in the scenario of two interfering WLAN APs, which are simulcasting bulky data to their associated individual stations in a lossy environment. In particular, we have proposed a collision based cooperative retransmission scheme. Our major contribution lies in the protocol design which well combines different interference-

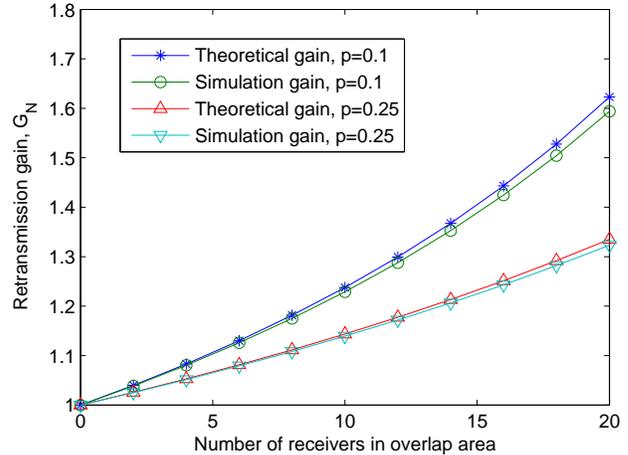


Fig. 5. Network retransmission gain G_N with $N = 10$ and $B = 1000$.

embracing techniques to solve the retransmission problem. We have also analyzed the performance gain of our proposed cooperative retransmission against the traditional ARQ scheme. Both theoretical analysis and simulations show that our proposed collision based retransmission method is able to reduce the number of retransmission of ARQ by up to 50%.

Although we focus on the scenario of two interfering WLAN APs, the proposed collision based cooperative retransmission scheme can be applied to any two interfering pairs of ‘sender-receiver’, which is quite common in WLANs, wireless mesh networks and wireless sensor networks. Our future work will be to extend the proposed scheme to more general scenarios such as a mixture of simulcasting and multicasting receivers and heterogeneous receivers.

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