MobiCom 2009 Poster: On coding concurrent transmissions in wireless networks *

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In this paper we identify a specific class of collisions called asymmetric collisions where the nature of collisions is different at the receivers of the colliding signals. We show that, with appropriate handling, asymmetric collisions allow the receiver to decode its intended reception successfully. Due to the natural combining of signals from multiple senders, the received symbol can be represented as a function of the transmitted symbols fc. We identify this property of concurrent coded wireless transmissions and propose a solution called collision coding to leverage such collisions.

I. Collision coding

I.A. Motivation

Wireless Local Area Networks provide tetherless connectivity and enable user mobility by using an unguided communication medium (i.e. air). However, the use of an unguided medium causes interference among co-channel signal transmissions, one the intended signal and the other an interfering signal, when they arrive simultaneously at a receiver. Interference typically renders the intended signal non-decodable and hence directly contributes to lowering the performance of the communication network. Hence several medium access techniques exist to either assign concurrent users to orthogonal time slots (e.g. Bit-Map protocol, Carrier Sense Multiple Access, TDMA) or to orthogonal frequencies (e.g. channels 1, 6, 11 in IEEE 802.11g). With increasing user density [3] and bandwidth requirements, the performance obtained by each individual user degrades significantly with the number of co-channel users because of shared use of communication resources. Hence, techniques that improve the concurrency of co-channel links are essential to improve network capacity.

I.B. Concept and illustration

When multiple senders transmit concurrently, the signals naturally combine in the channel after incurring channel impairments such as fading and attenuation. This signal superposition when translated to the bit level leads to the property that the decoded bit is a function of the transmitted bits depending on the modulation. We model the combination of symbols as a function called the *collision function* f_c. By characterizing this function and coding the transmitted symbols appropriately, concurrent links can be made to operate simultaneously.

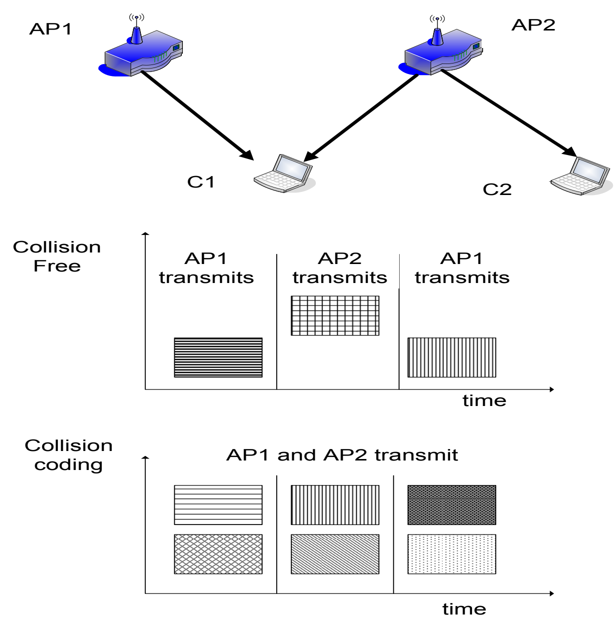

Figure 1: Illustrative Example

Consider the network topology shown in Fig. 1 where the access points AP1 and AP2 operate on the same channel and two clients $C1$ and $C2$ associated to $AP1$ and $AP2$ respectively. When $AP1$ and $AP2$ both transmit simultaneously to $C1$ and $C2$, the two transmissions collide at $C1$, but $C2$ receives a clear signal from $AP2$. Considering Amplitude Shift Keying (ASK) Modulation a '1' bit is represented by a high signal amplitude and a '0' bit is represented by sending a low amplitude signal. Conventional collision free scheduling would require the transmissions for C1 and C2 to be separated in time, since AP2's transmission would cause a collision at C1 rendering it unable to decode the packet sent by AP1. More

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C1/C2	00	01	10	11
00	011	011	011	100
01	101	101	010	101
10	110	001	110	110
11	111	111	111	111

C2	AP2
00	000
01	001
10	010
11	100

Figure 2: Coding Tables at AP1 and AP2

specifically, the resulting bit decoded at C1 for each of the four combination of bits transmitted from AP1 and AP2 is presented in Table I.B. Clearly $C1$ does not receive the intended bit from $AP1$ always. But interestingly, it can be observed that except when AP1 transmits a '0' and AP2 transmits a '1', the receiver C1 receives the correct bit (transmitted by its AP) even despite the collision. Overall, the bit error rate at C1 is 0.25.

Table 1: Success of transmissions

AP1	AP2	C1	C2	Successful ?
0	0	0	0	Yes
0	1	1	1	No
1	0	1	0	Yes
1	1	1	1	Yes

By analyzing the functional dependence between the transmitted and received bits, the collision function f_c at $C1$ is a binary 'OR' function of the bits transmitted from $AP1$ and $AP2$.

Collision coding: In the above example, the '01' bit combination ('0' from AP1 and '1' from AP2) is the harmful combination, where the receiver C1 does not receive the intended information. Hence, *if this combination were to be avoided by appropriately coding the data bit sequences, simultaneous information transfer to both C1 and C2 is achievable*. Consider the following coding strategy. Instead of transmitting the data packets destined for clients C1 and C2 as-is, AP1 and AP2 transmit coded versions of the packet according to Table in Fig. 2. Thus every two bits of information in d_1 and d_2 are appropriately mapped to a three bit codeword.

When the channel executes the "OR" operation on the coded bits, all combinations of codewords are still successfully decoded at C1 (and trivially at C2). Hence, by avoiding the combination of bits that cause a failure due to collision, this approach allows the three-bit codewords to be transmitted concurrently from AP1 and AP2 conveying two data bits each for C1 and C2. Thus, this scheme provides a $\frac{4}{3}$ i.e 1.33x improvement when compared to a collision free scheduler. We call this approach *Collision Coding*. The performance benefits of collision coding, while significant ($1.33x$ improvement over a collision free scheduler) even for a simple two AP topology also scales with the size of the topology providing $2x$ and $2.67x$ for three AP and four AP topologies, respectively. Additionally, we note that successful decoding is possible for different popular modulations and even when the colliding sequences do not use the same modulation.

II. Practical considerations

II.A. Proof of concept experiments

We first experimentally verify that the above coding approach works in practice using software radios in a real-life setting. The USRP [1] hardware and default GNURadio [2] software modules for packet transmission are used by implementing non-coherent ASK modulator and demodulators. Two USRPs act as the two APs and are synchronized to transmit by using the Network Time protocol along with triggered and high priority execution of the GNURadio code. The position of C1 and C2 are varied while maintaining the topology in Fig.1. The packet success rate at C1 averaged over 100 packets was observed to be around 0.5% without coding. But with the described coding scheme packet success improved to 98.1%. Clearly, collision coding ensures that the Bit Error rate remains below the threshold of acceptance (10^{-3}) thereby confirming that collision coding is feasible in real wireless channels.

II.B. Modulation and code design

While we presented the basic idea using Amplitude Shift Keying as the modulation, Collision Coding works with any modulation in principle. Collision Coding leverages the fact that when senders transmit concurrently, some symbol combinations are resolvable and some that are not and appropriately codes for them. While coding must be adapted to prevent *harmful* symbol combinations from occurring, the demodulation should be adapted to leverage concurrent senders. While we could design new modulation and demodulation algorithms that support collision coding, to remain compatible with existing modulation mechanisms, we describe how collision coding can be achieved using existing modulations with appropriate algorithms. The key design components to achieve this are (1) bit to symbol mapping at the transmitter and (2) the demodulation strategy at the receiver.

Assume that both AP1 and AP2 use Quadrature Phase Shift Keying (QPSK) as the underlying modulation. QPSK is popularly used in the 802.11 standards (abgn). Depending on the bit pair to be en-

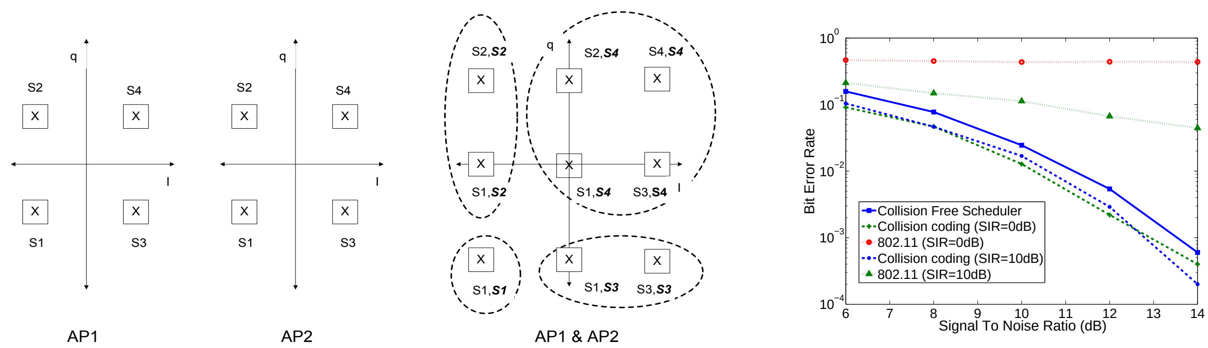

Figure 3: Collision coding equal modulations: 4-QAM illustration and simulation

coded i.e. $00, 01, 10, 11$, the transmitted symbols are chosen from a set $S = S_1, S_2, S_3, S_4$ where $S_1 = -1 - j, S_2 = -1 + j, S_3 = 1 - j, S_4 = 1 + j$ for bits $00, 01, 10, 11$ respectively. The symbols are shown pictorially using the constellation diagram in Figure 3 for both the single transmission case and for the concurrent transmission from AP1 and AP2. While there are 16 possible combinations, only nine of them are valid combinations which result in uniquely decodable (non overlapping) pairs. It can be observed that the concurrent symbol pairs that are allowed are given by the following nine pairs (S_1,S_1), (S_1,S_2), (S_1,S_3), (S_2,S_2), (S_3,S_3), (S_1,S_4), (S_2,S_4), (S_3,S_4), (S_4,S_4). The demodulation regions are represented by dotted lines in the Figure 3. The constellation diagram represents nine pairs with the property that (i) each of these pairs results in a unique constellation point (ii) the distance between the constellation points is not reduced compared to the original constellation. The minimum distance between valid constellation points determines the error performance and the larger this distance the better the decodability [5]. Thus the nine pairs provide a larger number of states without reducing the error performance compared to a single transmission. Consequently, they can be used to improve the capacity of concurrent links.

II.C. Synchronization

Collision coding, as described thus far, requires the transmitted bits to be synchronized to a symbol level. In 802.11 a/g networks, the symbol duration is 4 μs. Recent works [4] have shown how to achieve synchronization to the granularity of few tens of nanoseconds. Further, when collision coding is implemented in the hardware, much finer timing synchronization is achievable. Hence, we argue that the synchronization requirement is already addressed by several solutions in the literature. This leaves us with a residual synchronization error which might be sub-symbol and atmost one or two symbols. Such sub-symbol synchronization offsets would appear similar to multipath components of the transmitted symbol. Hence, they can be handled using existing equalization techniques [5].

II.D. Evaluation

We evaluate the Bit Error Rate performance of the 4-QAM collision coding scheme for the same two AP two client scenario using simulations based on an additive white Gaussian noise (AWGN) channel [5]. Figure 3 b) plots the BER at C1 as a function of SNR_a, the SNR from AP1 to C1 for 4-QAM modulation. The figure shows that Collision Coding allows concurrent transmissions while achieving an error performance that is close to a collision free scheduler. In addition, our experiments with software radios has also verified the practical feasibility and benefits of collision coding.

III. Conclusion and future work

In this paper, we propose a novel coding approach across links in a wireless network that encourages concurrent co-channel links and improves network capacity. While we verified the basic concept, there are several interesting items for future research such as algorithms to design codes for a network, generalization to all modulations and scheduling across links.

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