Attached-RTS: Eliminating an Exposed Terminal Problem in Wireless Networks

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Abstract—Leveraging concurrent transmission is a promising way to improve throughput in wireless networks. Existing media access control (MAC) protocols like carrier sense multiple access always try to minimize the number of concurrent transmissions to avoid collision, although collisions at sender sides are harmless to the overall performance. The reason for such conservative strategy is that those protocols cannot obtain accurate channel status (who is transmitting and receiving) with low cost. They can only avoid potential collisions through rough channel status (idle or busy). To obtain additional information in a cost-efficient way, we propose a novel coding scheme, Attachment Coding, to allow control information to be "attached" on data packet. Nodes then transmit two kinds of signals simultaneously, without degrading the effective throughput of the original data traffic. Based on Attachment Coding, we propose an Attached-RTS MAC (AR-MAC) to exploit exposed terminals for concurrent transmissions. The attached control information provides accurate channel status for nodes in real time. Therefore, nodes can identify exposed terminals and utilize them for concurrent transmission. We theoretically analyze the feasibility of Attachment Coding, and implement it on the GNU Radio testbed to further verify it. We also conduct extensive simulations to evaluate the performance of Attached-RTS. The experimental results show that by leveraging Attachment Coding, AR-MAC achieves up to 180 percent in dense deployed ad hoc networks.

Index Terms—Exposed terminal problem, interference cancelation, ad hoc network

1 Introduction

Wireless technologies have gained tremendous popularity in recent years, resulting in a dense deployment of wireless devices. Therefore, it is desired to utilize concurrent transmission to improve the overall throughput in wireless networks. However, current prevailing media access control (MAC) protocols are contention based [3], which always attempt to avoid potential collisions by reducing the number of concurrent transmissions, even though collision may not actually happen. Taking carrier sense multiple access (CSMA) protocol [12] as an example, a sender always listens on the carrier waves before transmitting to check whether the channel is busy or not. This sensing scheme can sometimes be too arbitrary, since whether a packet can be successfully decoded relies on channel conditions at the receiver side. But the receiver does not always experience the same noise and interference as the sender. As depicted in Fig. 1a, CSMA prevents Bob from transmitting to Alice, even though their transmission will not interfere current transmission between Dave and Coral. This problem is also known as an exposed terminal problem.

CSMA with collision avoidance (CSMA/CA) designs a handshake mechanism called RTS/CTS [12] to mitigate the exposed terminal problem. When a node hears a RTS without corresponding CTS feedback, it is presumed to be an exposed terminal, and its transmission is permitted. However, RTS/CTS not only has high cost but also leads to other problems like false blocking [2]. CMAP [3] deduces exposed terminals and excludes collided transmissions by consulting to a "conflict map." The map is constructed online using packet loss probability, making it not such reliable under poor channel condition. We argue that the above mechanisms are not capable of acquiring enough information of channel status with low cost to make the right decision (transmit or defer). We need a cost-efficient technique to provide more knowledge about transmission state of the channel, which can help MAC layer protocol make right access decision fast and accurate.

Recently, interference cancelation (IC) techniques [4], [5] have made significant progress to recover transmission errors caused by interference. This gives us an insight to propose a new coding scheme, Attachment Coding, to provide additional information we require cost effectively. Specifically, we modulate control information into special designed narrowband signals called *Attachment*. By intentionally injecting *Attachment* on one's data packet, others are capable of acquiring control information along with data. This attached manner is promising due to its ability to avoid additional bandwidth for control information. However, Attachment Coding is not easy to realize. First, how to combine *Attachment* and data into simultaneous transmission remains a concern. Second, receiver should be able to successfully detect and decode both *Attachment* and data information. Last, other nodes which also want *Attachment* should be capable of acquiring *Attachment* whenever they need.

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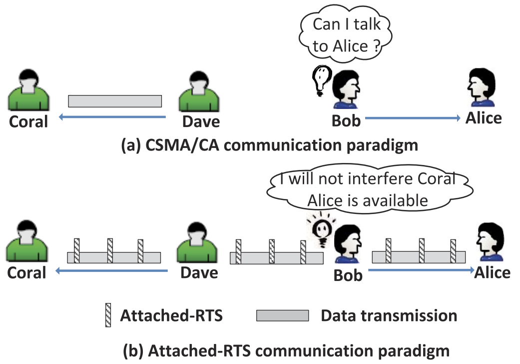

Fig. 1. (a) CSMA/CA communication paradigm. (b) Desired Attached-RTS communication system: control messages and data packets are transmitting together.

To demonstrate the effectiveness of Attachment Coding, we propose a new cross-layer design called Attached-RTS, which leverages exposed terminals for concurrent transmissions in distributed networks. Attached-RTS consists of two parts: *Attachment Coding* in a PHY layer and *Attached-RTS MAC (AR-MAC)* in an MAC layer. Attachment Coding attaches special designed RTS on data transmission, thus provides additional cue to authenticate current transmission. AR-MAC then guides nodes to identify exposed terminals through these authentications. As illustrated in Fig. 1b, when Bob wants to transmit to Alice, he overhears Attached-RTS on Dave's data packets and realizes that Dave is transmitting to Coral. After consulting to two-hop neighbor list, Bob figures out that he is an exposed terminal and conducts transmission immediately.

We verify the feasibility of Attachment Coding using GNU Radio testbed, and further evaluate the performance of Attached-RTS using NS-3. The experimental and simulation results in Section 4 show that Attachment Coding is feasible to transmit cost-effective control information. By utilizing Attachment Coding, Attached-RTS improves the aggregate throughput by 180 percent in ad hoc networks and 160 percent in mesh networks over CSMA. In summary, the main contributions of this paper over existing protocols in distributed WLANs are as follows:

- We present a novel encoding and decoding scheme (Attachment Coding) that enables node to add modulated control transmission along with data transmission on the same frequency band.
- We propose a new MAC protocol (AR-MAC) that builds on top of the new coding scheme to identify and utilize exposed terminals for maximizing concurrent transmissions.
- We theoretically analyze the feasibility of Attachment Coding, and implement real-time experiments using GNU Radio testbed and conduct extensive simulations using NS-3 to evaluate the performance of the new communication system (Attached-RTS).

The rest of this paper is organized as follows: In Section 2, the design of Attachment Coding is presented, which is followed by the overall architecture of AR-MAC. In Section 4, we analyze the feasibility of Attachment Coding and the performance AR-MAC by extensive experiments and simulations. We give the related work in Section 5 and present the conclusion in Section 6.

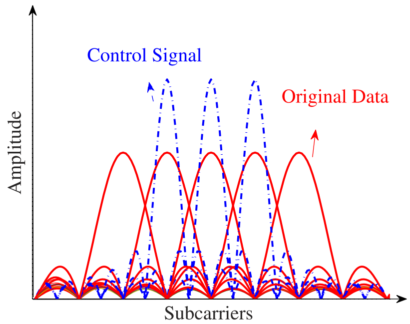

Fig. 2. An illustration of Attachment Coding to transmit control messages and data packets together.

2 Attachment Coding

In this section, we describe the overall architecture in an Attachment Coding-enabled communication system. Attachment Coding is built on top of an OFDM-based system. The primer for OFDM modulation is in the supplemental files, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2012.228. Here, we demonstrate the detailed design of Attachment Coding, which includes two components: 1) attachment modulation and demodulation, and 2) attachment cancelation and data recovery.

2.1 Attachment Modulation/Demodulation

For *Attachment* modulation/demodulation, to avoid interference with each other, each attached signal should have a bandwidth narrow enough to be included into a single subcarrier even with frequency offset. Fig. 2 illustrates the main idea, that is, attaching narrow-band signals on data symbols. As a payoff, the capacity of *Attachment* is small. However, this capacity will be acceptable because *Attachment* for control message can be compressed simple and efficient. Physical layer signaling with binary amplitude modulation is a good example. One attached signal on a particular subcarrier can represent certain information (in Section 3.2.1). To detect an attached signal on a particular subcarrier, we adopt a simple but efficient scheme based on energy detection. According to energy distribution, high throughput transmissions and white noise spread their energy over the spectrum, while narrow-band attached signal has relatively high energy levels. Therefore, when we detect relatively high level energy on a particular subcarrier, we can assume that there is an attached signal on that subcarrier. After detecting the attached signals, node can obtain corresponding control messages.

2.2 Attachment Cancelation and Data Recovery

For attachment cancelation and data recovery, as row signals combing attached signals and data packets are not directly decodable at receiver side, an IC technique has to be leveraged on subcarriers which carry attached signals. We use a training sequence, which is transmitted at the beginning of each packet to obtain channel state information (CSI) [24] for channel estimation, to perform attachment cancelation. Since correlation exists among subcarriers in the frequency domain, CSI of a particular subcarrier can be interpolated with adjacent ones. Therefore, it is feasible to vacate a few of subcarriers [8]. We call these subcarriers "clean" because ideally there is no signal except noise

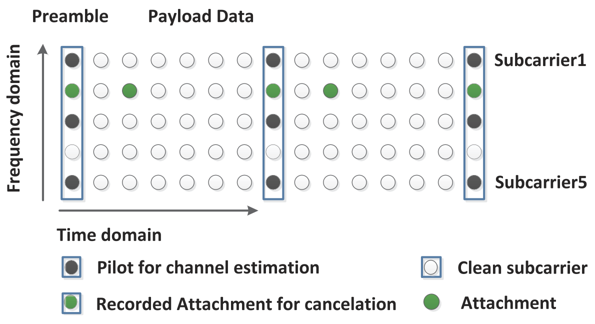

Fig. 3. Illustrated example of attached control messages.

detected at the receiver side. Taking advantage of these clean subcarriers, we can record each attached signal in a training sequence for the purpose of attachment cancelation and data recovery in subsequent payload data packet. Specifically, the received signal with *Attachments* on clean subcarriers of a training sequence can be expressed as

$$y^{clean}[t] = y_{attach}[t] + n[t]. \tag{1}$$

Accordingly, the received signal in subsequent data symbol with both data and attached signals can be expressed as

$$y^{raw}[t] = y_{\text{data}}[t] + y_{attach}[t] + n[t], \tag{2}$$

where $y_{attach}[t] = H \times Attach[t]$ and $y_{data}[t] = H \times Data[t]$ are attached signals and data signals, respectively, after traversing channels to the receiver. H refers to the corresponding channel impulse response which can be calculated using a training sequence and $n[t]$ refers to a random complex noise. Therefore, the original data signal can be recovered by canceling the attached signal from the received signal in data symbol, that is

$$Data_i[t] = \frac{y_i^{raw}[t] - y_i^{clean}[t]}{H}. \tag{3}$$

Fig. 3 illustrates Attachment Coding in time/frequency domain. A training sequence carries the recording attached signals for cancelation and subsequent data packet carries the actually coordination signals. The feasibility of Attachment Coding is analyzed in the supplemental files, available online, serving as design principle for Attachment Coding.

3 AR-MAC Protocol

To demonstrate the effectiveness of Attachment Coding, we present a cross-layer design, AR-MAC. AR-MAC builds on top of Attachment Coding, which aims to solve the exposed terminal problem in distributed wireless networks. First, we give an overview and design challenges of AR-MAC. Detailed modules are then presented to see how we address these challenges. Finally, we talk about some points related to an AR-MAC design.

3.1 AR-MAC Overview

To identify whether a node is exposed terminal or not in a distributed network, we need two kinds of information: 1) the ongoing sender-receiver pairs; and 2) the neighborhood information within two-hop collision domain. As illustrated in Fig. 4, nodes can be characterized into two types: current sender-receiver pairs and intended sender-receiver pairs. Suppose an intended sender (IS) Bob has some packets to transmit, he should guarantee that his intended receiver Alice or Lucy is available and other current receivers (CRs) like Coral will not be interfered by his transmission.

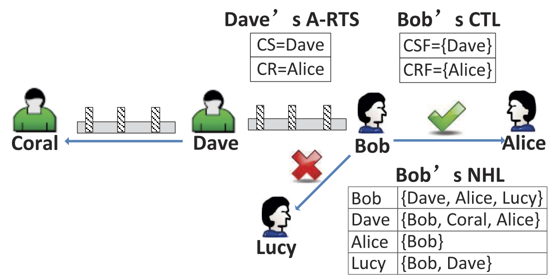

Fig. 4. Overview of Attached-RTS.

Based on the above observation, we propose AR-MAC, which utilizes Attachment Coding and neighborhood list to provide the above two information, including the ongoing transmission on air, and the two-hop neighborhood list. Without loss of generality, we assume that the interference and reception range are equal. To obtain the information of current transmissions, each sender modulates its transmission information into *Attachments* (A-RTS) (like who are the sender and receiver for this transmission). To obtain the information of two-hop neighborhood, nodes can periodically be broadcasting their one-hop neighborhood list in their vicinity [3], either broadcasting stand-alone packets for the list, or piggybacking the list with routing beacons.

The design principle of AR-MAC is simple and efficient. However, there remains several implementation challenges when bring AR-MAC into practice:

- First, *Attachment* cannot carry too much information due to its limited bandwidth. Thus, the format of A-RTS should be designed efficiently.
- Second, distributed networks are always unsynchronized with variable-length packet. Thus, it is difficult for a node to obtain A-RTS whenever it needs.
- Last, any strategy that tries to utilize exposed terminals has to handle ACK collision with other data transmissions, and data transmissions can also collide with themselves. These collisions should be treated carefully to increase PRR.

To address these challenges, AR-MAC consists of two stages: RTS sense and collision resolution. Every node first goes through RTS sense to contend for channel access. Afterward, collision resolution will handle collisions among different kinds of transmissions.

3.2 RTS Sense

RTS sense initiates a normal contention for data transmission opportunity. Instead of carrier sense in CSMA that detects carrier waves before trying to send, RTS sense simply listens to A-RTS signals attached on carrier waves. RTS sense contains two parts: RTS attachment and channel access decision.

3.2.1 *RTS Attachment*

To modulate the current transmission information into A-RTS, a specialized hash format is adopted. Each A-RTS

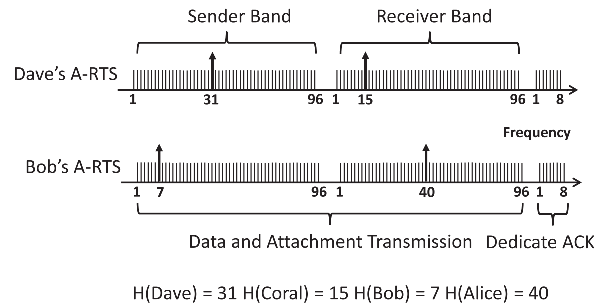

Fig. 5. AR-MAC splits subcarriers into sender and receiver bands to represent A-RTS.

contains the hash values of the corresponding sender/receiver's IDs. We utilize this hash function due to two reasons. First, different nodes should have exclusive subcarriers for their A-RTSs to avoid interference with each other. However, since the number of subcarriers is limited, it is difficult to allocate different subcarriers to different nodes in a decentralized manner. Second, it is impossible to modulate the whole MAC address into A-RTS frame due to high bandwidth cost. Therefore, we only use a hash value to represent each node. Specifically, the whole subcarriers are split into sender/receiver band, as shown in Fig. 5. In each band, a membership vector of n subcarriers is used to represent sender/receiver information. This hash format guarantees A-RTS to be modulated into only one OFDM symbol (256-point FFT in AR-MAC). Before each transmission, sender hashes its ID and its receiver's ID into two values between $0-(n-1)$ respectively. Then, the corresponding subcarriers in sender and receiver bands will carry a "1" bit. Each node only needs to acquire the information within two-hop neighborhood (assuming node degree of 5). With a reasonably sized n (e.g., 96 in AR-MAC), hash value collisions should be small. Moreover, we will prove even with hash collisions that nodes can always make the right channel access decision in Section 3.4.2. Utilizing a hash value, A-RTS actually only has two bits, one is to represent sender and the other is to represent receiver. As shown in Fig. 5, Dave chooses subcarrier 31 in sender band and subcarrier 15 in receiver band according to the hash values. Then, it transmits two narrow-band signals on these two subcarriers as its A-RTS. Then, other nodes within the neighborhood can use energy detection to decode A-RTS and obtain the sender-receiver information from it.

For ISs, it is essential to overhear A-RTS signals whenever they need, since they may begin to listen to A-RTS from any part of a packet in an unsynchronized manner. To address this issue, we propose a *cyclic attachment* mechanism that ensures A-RTS can be grasped at any moment. Since A-RTS can be modulated into just one data symbol, we repeat A-RTS on every data symbol within a whole packet. As illustrated in Fig. 6, no matter which part of the packet a node starts to monitor, the entire A-RTS signal can be retained as long as it monitors more than one symbol duration. Even A-RTS signal is not captured exactly from the beginning of a data symbol, the missing portion of a signal can be retained from next symbol due to cyclic property.

3.2.2 Channel Access Decision

To make channel access decision, AR-MAC requires each node to maintain two distributed hash lists: current

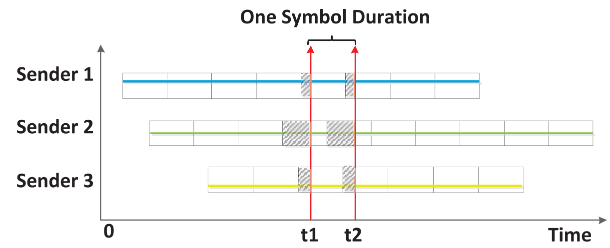

Fig. 6. Cyclic Attached-RTS.

transmission list (CTL) and neighborhood hash list (NHL). A CTL consists of two fields: current sender field (CSF) and current receiver field (CRF). After a node detecting A-RTS signals, it decodes all the hash values of CS-CR pairs' IDs and fills them into CSF and CRF, respectively. NHL also includes two fields: first-hop neighborhood field (FNF) and second-hop neighborhood field (SNF). FNF encodes all the hash values of nodes' IDs within one-hop neighborhood. SNF is actually a table with entries of all first-hop neighbors' IDs pointing to their FNFs, as illustrated in Fig. 4. Nodes periodically broadcast their FNFs to all one-hop neighbors.

Channel access decision is made as follows: When Bob wants to send packets to Alice, he will first listen to A-RTS signals on air and add all the CSs and CRs into CSF and CRF, respectively. After obtaining CTL in hand, Bob will extract the neighborhood information of Alice, say SNF_{Alice} from SNF and checks the following metric:

$$(CRF \cap FNF == \emptyset) \cap (CSF \cap SNF_{Alice} == \emptyset).$$

If this metric returns true, Bob can confirm his transmission and send packets to Alice immediately; otherwise, Bob need to defer his transmission until the above metric is satisfied.

3.3 Collision Resolution

Collision may happen after a packet has been transmitted, such as ACK colliding with data transmission, or data transmissions colliding among themselves. Collision resolution employs two strategies to reduce these collisions: dedicated ACK and fast retransmission.

3.3.1 Dedicated ACK

When there are multiple concurrent transmissions within the same collision domain, ACK has a high likelihood to collide with other data transmissions at the exposed terminal senders. This can be illustrated in Fig. 1, where the ACK from receiver z to sender u can collide at u with a data transmission from x to y. Attached-RTS proposes dedicated ACK to handle this kind of collisions. A small portion of the subcarriers are split from the whole channel and used only for ACK transmission. Since ACK and data packets are transmitted in separated subcarriers, they will no longer collide at the exposed terminal senders.

This strategy does not sacrifice bandwidth much for the reason that ACK transmission is simply moved from time domain to frequency domain and transmitted with data packets simultaneously using different subcarriers. In AR-MAC, the payoff subcarrier of ACK to data is $\frac{8 subcarriers}{192 subcarriers} \approx 4.2\%$. Comparing with state-of-the-art 802.11a/g with bit rate 54 Mbps, the payoff time of ACK to data is $\frac{24\,\mu s}{248\,\mu s} \approx 9.7\%$. In

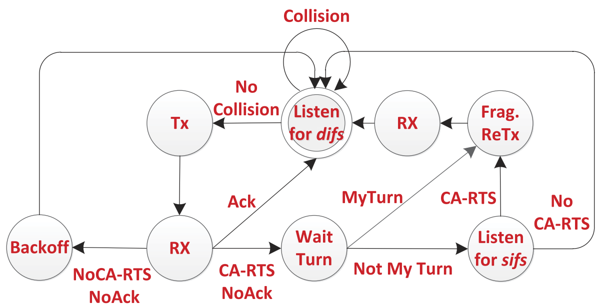

Fig. 7. State transition diagram of AR-MAC.

addition, ACK is shorter enough than data packets, ensuring that ACKs themselves will not collide with each other.

However, we may concern that dedicated ACK may experience narrow-band fading, and results in transmission failure. To overcome the performance loss due to narrow-band fading, during the network initialization, we will estimate CSI [24] and choose the subcarriers that with the best channel quality to dedicated ACK. When the network operates, we recheck CSI after each certain period, and reassign the best ones for dedicated ACK. This adaptive manner alleviates the effect of narrow-band fading to some extent. More sophisticated approaches are left as future work to increase the packet reception rate.

3.3.2 Fast Retransmission

Collisions also happen among simultaneous transmissions. When there are at least two simultaneous transmissions within the same collision domain, none of the ISs has time to listen to other's A-RTS for one symbol duration. Thus, collision is inevitable. AR-MAC designs a fast retransmission round (FRR) for these collided parties. FRR has higher priority than normal RTS sense (NRS) to facilitate collided senders finish their retransmission first. The priority is achieved by separating transmissions in FRR by short interframe space, instead of the original DCF interframe space (DIFS) in NRS. During FRR, every collided sender can retransmit once. The retransmission order is based on the number of A-RTSs sensed from all collided parities. We use an example in supplemental files, available online, to better illustrate the idea of fast retransmission.

The state transition diagram for AR-MAC is shown in Fig. 7. A sender first listens to the A-RTSs on air. If there are no collided A-RTSs for DIFS period, the sender can conduct transmission. Upon receiving an ACK, this transmission is considered as successful. Otherwise, the sender will counter the number of A-RTSs after transmission, and wait for its turn for retransmission. If no A-RTS is heard, it considers itself as hidden terminal with a high probability and backoffs to avoid future collision.

3.4 Points of Discussion

We finish the description of AR-MAC with a few points of discussion. Other discussions are provided in supplemental files, available online.

3.4.1 Influence of Hash List Collision

Since AR-MAC utilizes a hash value to represent node ID, one possible question is that whether hash collision will result in performance loss. First, the probability of hash collision is quite low. With node density of 10 and key space of hash function equals to 100, the probability of pair hash collision is around 10 percent. This probability becomes even smaller with more collisions. Second, even hash collision happens, AR-MAC has a conservative solution to avoid data packet collision. It asks node to always defer transmission when it assumes hash collision happens.

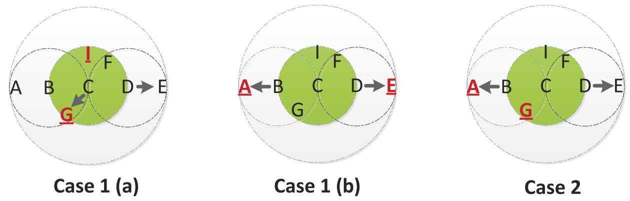

Fig. 8. Illustrated example of pair hash list collision.

However, this solution may introduce a very small probability of losing transmission opportunity. We use a hypothetical example with pair collision in receiver field for illustration. As shown in Fig. 8, the locations of nodes are already given. Nodes are distributed with equal distance relevant to their transmission range. Assuming node i has a hash value of $H(i)$, there are two cases of pair collision: collision within the same hop (e.g., $H(A) = H(E)$ or $H(F) = H(G)$), and collision between different hops (e.g., $H(A) = H(G)$). In case 1, hash collision results in the same action. Specifically, in Case 1(a), C will defer transmitting to D in the presence of current transmission from D to E. In Case 1(b), B will conduct transmission in the presence of current transmission from D to E. Therefore, AR-MAC does not have performance loss. In Case 2, since B is not able to distinguish A from G, it will defer transmission to A, which will waste exposed terminal opportunity. The probability of performance loss is derived using geometry representation in Case 2, where the entire two-hop area is unit 1. Nodes have three statuses: sending, receiving, and idle, each with probability of 1/3. Given a node C, and a hash collision pair A/G with probability 1, P_{loss} should satisfy the following conditions: 1) A is receiving data packet in white area, $P(A) = \frac{3}{4} \times \frac{1}{3}$; 2) G is idle in green area without intersection with red area, $P(G) = \frac{1}{4} \times \frac{2}{3} \times \frac{1}{3}$. Then, $P_{Loss} = P(A) \times P(G) = \frac{1}{72}$. Using the similar methodology, more number of collisions can be proved to have even small probability of performance loss. Combined with the above two considerations, the real effects of hash collision become insignificant.

3.4.2 Cost of Attachment Transmission

We claim that attachment transmission has the significant advantage to send the control information and data packets in a cost effective way. It is worth pointing out that "cost" represents bandwidth resource, as discussed in [5], [15], [16], [22]. In fact, since self-jamming and IC is adopted, energy consumption increases accordingly. An encoding and decoding process has also become more complex than the traditional communication system, which may increase the processing time and transmission delay. Therefore, how to design an energy-efficient and delay-sensitive Attachment Coding paradigm will be left as our future work.

4 Performance Evaluation

In this section, we first evaluate the feasibility of Attachment Coding by using our prototype implementation, which is

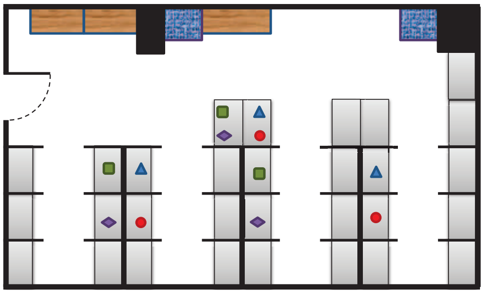

Fig. 9. Experimental environment (three sets of the four nodes' locations are illustrated as an example).

built on an indoor environment. The detailed system implementation is provided in supplemental files, available online. Then, we use NS-3 to study the performance of Attached-RTS over two state-of-the-art approaches: 802.11 MAC (including carrier sense on and carrier sense off), and CMAP [3] under various topologies. Our experiment results show that Attachment Coding can work quite well; in the meantime, it will not impact the original data transmission much. Our simulation results show that comparing with 802.11 CSMA, Attached-RTS achieves up to 180 percent performance gain under dense deployed ad hoc networks. Comparing with CMAP, Attached-RTS works better in a mobile environment, achieving a throughput gain up to 150 percent.

4.1 Feasibility of Attachment Coding

In this part, we conduct real-time experiments to evaluate the feasibility of Attachment Coding. The evaluation follows two aspects: 1) whether data transmission can be reliability decoded in the presence of attachment transmission; and 2) whether we can successfully detect attachment transmission and obtain the information.

Reliability of data transmission: To evaluate the reliability of data transmission under the impact of attachment transmission, we measure the decodability of the data receiver with and without attachment transmission. Here, a four-node setting is configured, i.e., two nodes for data transmission and two nodes for attachment transmission. As shown in Fig. 9, we conduct the experiment in our office, a typical real-world environment with size $5\ \mathrm{m} \times 8\ \mathrm{m}$. The data receiver is in the transmission range of both the data sender and the attachment sender. We let the data sender transmit normal packet to the data receiver, and simultaneously the attachment sender transmit *Attachments* to the attachment receiver. We compute the PRR at data receiver side under various SNRs with and with jamming, respectively. Each run transfers 2,500 packets, and repeats 10 times for each value of SNR.

We plot the PRR of data receiver with/without attachment transmission as a function of the received SNR at data sender side from 4 to 20 dB in Fig. 10. We can see that when the SNR exceeds certain threshold, i.e., 10 dB, the PRRs with attachment transmission are almost the same as those without attachment transmission. There is a little performance degradation when the SNR is smaller than 10 dB, which, however, can be acceptable, since the typical working range of SNR region for 802.11 is 10-30 dB [19]. These results verify that attachment transmission has little influence on data transmission. It is noticed that these

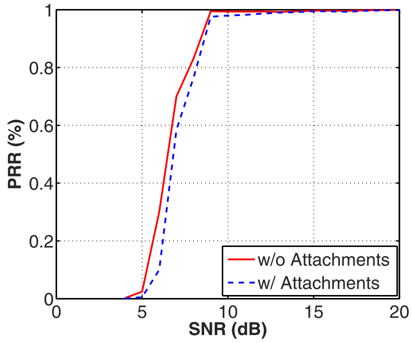

Fig. 10. Decodability of data transmission with/without attachment transmission under different SNRs.

experimental results are not as good as theoretical analysis in the supplemental files, available online. This results from two reasons. On one hand, USRP has certain limitations in strict timing and accurate sampling due to software-defined signal processing. On the other hand, our implementation runs in a public user space in the unlicensed 2.4 GHz range. Therefore, there must be some external interference that cannot be avoided.

In the next step, we evaluate the impact of number of concurrent attachment transmissions on the decodability of the data receiver. We use a similar setting to evaluate the PRR of the data receiver but with different number of concurrent attachment senders varying from 1 to 6. We assign each attachment sender a unique subcarrier for attachment transmission in this experiment, which are Subcarrier 1, 3, 5, 7, 9, and 17.

We plot the PRRs under different number of attachment transmissions with SNR 11 and 15 dB in Fig. 11. We can see that the performance losses are all under 10^{-2}, even with six concurrent attachment transmissions, which are relatively small. It is noticed that according to the theoretical analysis in the supplemental files, available online, the performance loss is expected to increase as the number of concurrent attachment transmissions increase. However, the experimental results show that the performance loss varies randomly under different number of concurrent attachment transmissions. This difference between the practical and the theoretical results may due to the processing capability of USRP2 hardware.

Feasibility of attachment transmission: To evaluate the performance of attachment transmission, we measure the

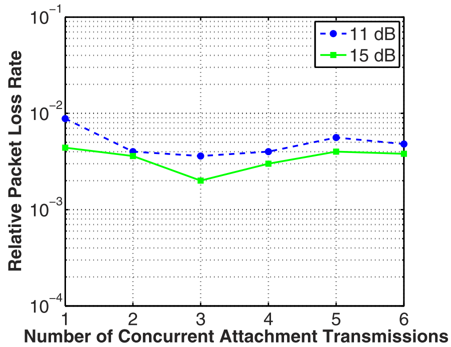

Fig. 11. Impact of number of concurrent attachment transmission under different SNRs.

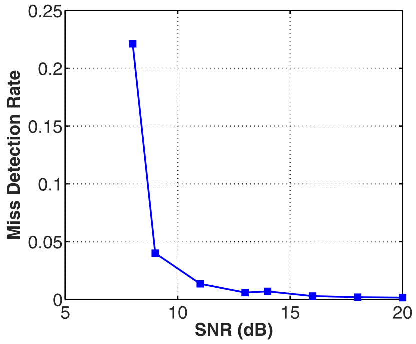

Fig. 12. Miss detection rate under different SNRs.

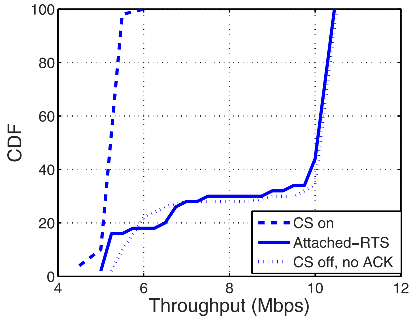

Fig. 14. Aggregate throughput of exposed terminal configuration.

detection accuracy at the attachment receiver side, which is, whether the attachment receiver can correctly detect an *Attachment* and decode the attached control information. There are two aspects that influence the detection accuracy: miss detection rate (P_{miss}) and false alarm rate (P_{false}), both of which will result in decoding failure. Here, we still use a four-node setting, i.e., two nodes for data transmission and two nodes for attachment transmission. We let the attachment sender keep transmitting *Attachments* in the presence of data transmission, then PRR is computed under various SNRs of the *Attachments* signal ranging from 8 to 20 dB. Each run transfers 2,500 packets, and for each value of SNR, the experiment is repeated 10 times.

According to the theoretical analysis in the supplemental files, available online, we expect that the P_{false} is very small. From the experimental results, we find that there is almost no P_{false} for all runs. Therefore, we only plot the results of P_{miss} in Fig. 12. We can see that when SNR > 13 dB, P_{miss} can be controlled within 1 percent, which results in a detection accuracy of more than 99 percent.

4.2 Performance of AR-MAC

Due to the latency constraint of USRP2, we are not allowed to conduct real-time evaluation of the system throughout. Therefore, in this section, we present the simulation results for the performance of Attached-RTS using NS-3. In the following simulation scenarios, channel bandwidth is 20 Mbps, with 256-point FFT OFDM modulation. The propagation model is log distance propagation. We use 192 and 8 subcarriers for data and ACK transmission, respectively. Detailed parameters follow the specification of 802.11a. Each simulation lasts 50 seconds. The total number of nonduplicate data packets successfully received by all the designated receivers per second is calculated as the aggregate throughput. We compare Attached-RTS to two settings of 802.11 MAC: carrier sense on (considered as "status quo") and carrier sense off (considered as "ideal case" for exposed terminals) in baseline topologies to see whether Attached-RTS can function correctly. Then, we compare Attached-RTS with 802.11 CSMA (carrier sense on) and CMAP to see the performance gain.

4.2.1 *Baseline Topology*

In this part, we evaluate the performance of Attached-RTS with two sender-receiver pairs in three simple topologies, as illustrated in Figs. 13b, 13c, and 13d. The goal is to establish a baseline for our evaluation. Specifically, we are going to figure out: 1) whether Attached-RTS can fully utilize concurrent transmissions in exposed terminal configuration; 2) whether Attached-RTS can avoid interference in interfering transmission configuration; and 3) whether Attached-RTS degrades performance in hidden terminal configuration. We select the above three configurations according to the principles described in Fig. 13, from a general 50 nodes topology with random distribution and degree of 12, as depicted in Fig. 13a. Each configuration is repeated 50 times, and each time we choose different sender-receiver pairs. The selection principles are defined based on PRR and signal strength, which are trained in advance and recorded for each link.

Exposed terminal topology: In this topology, we evaluate whether Attached-RTS can leverage exposed terminal for concurrent transmissions. The performance for CS on, CS off, and Attached-RTS is depicted in Fig. 14, where the CDF of aggregate throughput is across 50 exposed terminal configurations randomly chosen from all possible configurations. With CS on, most of the link pairs only achieve single link throughout of 5 Mbps. With CS off and ACK disabled, 25 percent of link pairs achieve little more than single link throughput, revealing that these links are not actually exposed terminals. For the rest 75 percent of the link pairs, CS off leverages exposed terminals to achieve

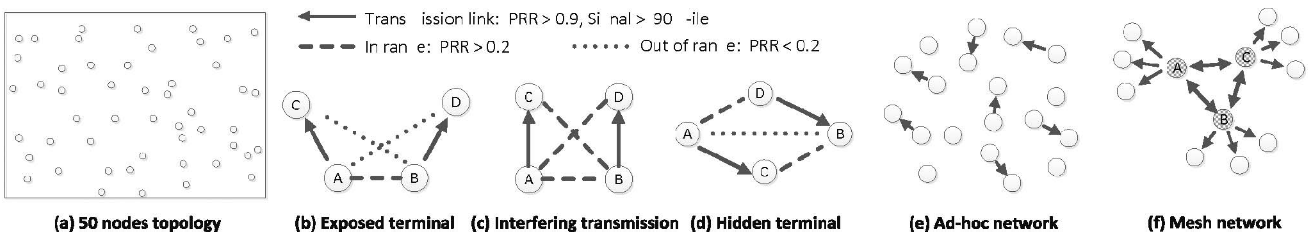

Fig. 13. Topologies overview, with 50 nodes basic testbed (a), base line topology (b), (c), (d) in Section 4.2.1, and practical networks (e), (f) in Section 4.2.2. Link constraints are included in the figure.

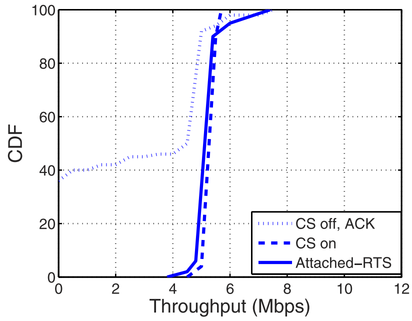

Fig. 15. Aggregate throughput of interfering transmission configuration.

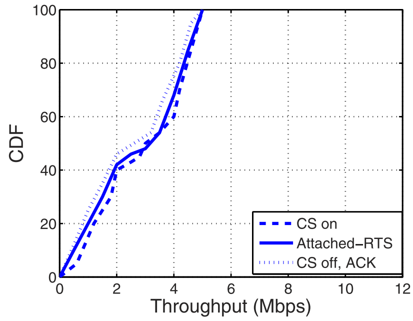

Fig. 16. Aggregate throughput of hidden terminal configuration.

double link throughput up to 10.5 Mbps. Attached-RTS well traces the curve of CS off indicating that through A-RTS sense, Attached-RTS can successfully identify exposed terminals and fully utilize them (B to D and A to C) for concurrent transmission. Since CS on can only leverage one pair of nodes for transmission (either A to C or B to D), AR-MAC improves throughput to approximately 200 percent over CS on. Note that Attached-RTS has little performance deduction comparing with CS off, about 0.25 Mbps. This is because ACK is disabled in CS off but Attached-RTS has ACK overhead to the overall throughput.

Interfering transmission topology: In this topology, we evaluate whether Attached-RTS can identify interfering transmission and defer transmission to avoid collision. We depict the CDF of aggregate throughput across 50 interfering transmission configurations randomly chosen from all possible configurations in Fig. 15. CS off achieves zero throughput for 40 percent of the link pairs, since concurrent transmissions are completely corrupted by each other. For the rest 60 percent of link pairs, deleterious simultaneous transfers give CS off poor performance. Meanwhile, Attached-RTS correctly figures out interfering transmissions and guides each link pair to transmit one after the other, thus achieves almost single link throughout as carrier sense on. There are 5 percent of link pairs that have throughput degradation for Attached-RTS comparing with CS on. This is because two link pairs may transmit simultaneously, making RTS sense enable to detect collision. However, the throughput degradation is very small (about 0.3 Mbps), evidencing that Attached-RTS's FRR can avoid further collision and let collided nodes recover as soon as possible. Also, the *No-CSRTS-Backoff* strategy precludes some hidden terminals from transaminating all the time. There are also 8 percent of link pairs better to transmit concurrently (on top of the figure), since CS off can achieve double link throughput. Attached-RTS quickly trace the curve of CS off with these links pairs.

Hidden terminal topology: In this topology, we are going to evaluate whether Attached-RTS can identify interfering transmission and defer transmission to avoid collision. We depict the throughput distribution across 50 hidden terminal configurations in Fig. 16, which shows that Attached-RTS, CS on and off have comparable throughout. This evidences Attached-RTS can deduce hidden terminal with a certain probability using collision resolution, and thus do not degrade performance in the presence of hidden terminals.

4.2.2 Practical Networks

In this part, we evaluate the performance of Attached-RTS in practical networks with multiple sender-receiver pairs. Ad hoc networks [21] and mesh networks [20] are considered to be representative for realistic networks, since it is nontrivial to obtain cost-effective control information in such decentralized or partial decentralized networks. Our simulations also model the CSMA, MAC, and CMAP. For the CMAP, our simulator uses a similar setting as [3] in both ad hoc and mesh networks.

Ad hoc networks: In this part, we quantify the performance of Attached-RTS in ad hoc networks, as illustrated in Fig. 13e, where nodes are distributed and unsynchronized. We model two kinds of ad hoc networks: nodes with fixed location (static ad hoc networks) and nodes with mobile location (mobile ad hoc networks). For mobile ad hoc network, we use GaussMarkoveMobilityModel as the mobility model. Concurrency is better to be leveraged in ad hoc networks, especially with high node density and heavy traffic load [7]. We still use 50 nodes topology in Fig. 13a, choosing 6, 8, 10, and 12 concurrent senders as four configurations. Each configuration runs 50 times, each time with different senders transmitting simultaneously with no more constrains.

Fig. 17 depicts the average aggregate throughput for Attached-RTS, CSMA, and CMAP in static ad hoc networks with different number of concurrent transmissions. By exploiting concurrent transmissions, Attached-RTS improves the aggregate throughput over CSMA by between $20\%(N = 6)$ and $78\%(N = 8)$. When number of concurrent transmissions increases, exposed terminals increases along with hidden terminals. Attached-RTS utilizes exposed terminal opportunities to increase

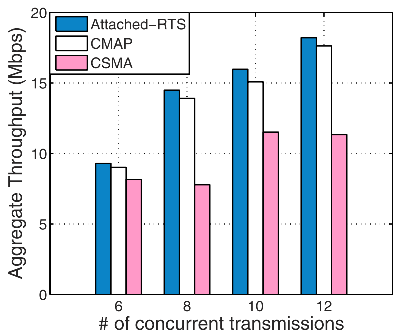

Fig. 17. Aggregate throughput in static ad hoc networks with different # of concurrent transmissions.

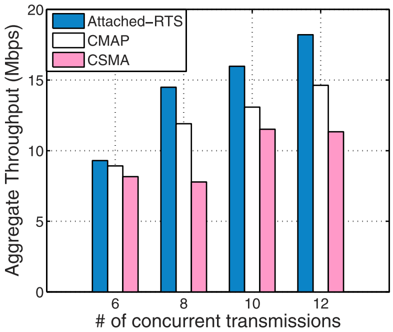

Fig. 18. Aggregate throughput in mobile ad hoc networks with different # of concurrent transmissions.

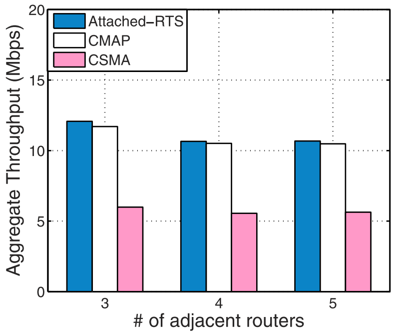

Fig. 19. Aggregate throughput in mesh networks with different # of adjacent routers, each with three clients.

throughout without degrading performance in the presence of hidden terminals. CMAP also explores concurrent transmission well, and achieves similar performance with Attached-RTS. However, it does have little performance degradation, which results from the construction of "conflict map" at the initialization of the network. Since Attached-RTS utilizes broadcasting through routing, it does not need to consume extra resource to obtain the neighbor information. Fig. 18 shows the average aggregate throughput for Attached-RTS, CSMA, and CMAP in mobile ad hoc networks with different number of concurrent transmissions. We can find that the performance of CSMA is rather poor, and CMAP cannot deal well with mobility. In the meantime, Attached-RTS can achieve up to $30\%(N = 8)$ performance gain over CMAP, verifying that Attached-RTS does not need to consume extra resource to identify exposed terminals.

Mesh networks: In this part, we present an evaluation of Attached-RTS over wireless mesh network (WMN), as depicted in Fig. 13e. Nodes A, B, and C are served as wireless routers, responsible for communicating with their clients A_i, B_i, and C_i. In WMN, wireless routers are very likely to be exposed terminal to each one another. Therefore, concurrency is also desired. We let the routers keep sending packets to one of their clients (i.e., A to A_i), and then compute the aggregate throughput across at all clients (A_i, B_i, and C_i). The number of adjacent routers is set to 3, 4, and 5 as three configurations. Each configuration runs 50 times with different clients.

Fig. 19 shows the result of average aggregate throughput for different number of adjacent routers. Attached-RTS improves the throughput between 180 and 210 percent over CSMA, as CSMA can only conduct one transmission in such topologies. Meanwhile, CMAP also explores concurrent transmission as our design. It only has little performance deduction due to the construction of "conflict map." The above topologies cannot represent arbitrary mesh networks. However, from the simulations, we believe that by utilizing concurrent transmissions, the performance of multihop mesh networks can be greatly improved. Moreover, higher layer protocol such as routing and scheduling can be even rethought to leverage the benefit of concurrent transmissions.

We also conduct simulations for AR-MAC under variable transmission rate. The detailed evaluation is in the supplemental files, available online. There are also discussions on the situation that the transmission range and interference range are not equal. We provide some simple solutions to address the problems raised by increasing data rate.

5 Related Work

Utilizing exposed terminals for concurrent transmission is considered to be a promising way to increase throughput [9], [10]. In [11], Judd observes that in a high load wireless network, different clients connect to different routers can often result in exposed terminals, indicating that exposed terminals should be well leveraged. CMAP [3] proposes a "conflict map" to deduce exposed terminals. A special header/trailer is designed for receivers to figure out interferers and allow exposed terminals to transmit concurrently. However, its packets are required comparable length for header/trailer decoding. Also, interferers are decided by loss probabilities. Unlike CAMP, Attached-RTS supports variable length packets. It can also identify exposed terminals fast and accurate using *Attachment* sense.

Recently, PHY layer techniques have been utilized to assist MAC layer protocol. In [13], the author utilize a PHY layer ACK to reduce the overhead of a traditional link layer ACK. In [14], PHY layer RTS/CTS is proposed for multi-round leader election and address a hidden terminal problem. Attached-RTS similarly shares the idea of PHY signaling, but differs from the above approaches that it enables a PHY layer control messages to be transmitted simultaneously and harmlessly with data traffic. Moreover, it utilizes this cost-effective control message to solve exposed terminal problems. Another approach to combine different coding schemes into one transmission is hierarchical modulation [17], where base-layer and enhancement-layer symbols are synchronously overplayed. Unlike hierarchical modulation, which uses modulation constellation to provide different types of QoS in digital TV broadcast, Attached-RTS utilizes IC to achieve the broader goal of enabling control information to be "attached" on data transmission for cost-effective coordination. Handling the exposed terminal problem is one of its application scenarios. Side channel [15] and $h\mathrm{jam}$ [16] both add jamming signals on other users' packets, in this way they can provide access request for certain authority in centralized networks. Attached-RTS, however, simply attaches control information on one's own data packets. Therefore, it can provide a flexible PHY layer information for higher layer protocol, which is more applicable and reliable.

6 Conclusion

In this paper, we propose a novel Attachment Coding scheme to attach control information on data traffic. This coding scheme enables data transmission along with control transmission, without degrading the throughput for original data traffic. To illustrate the effectiveness of Attachment Coding, we propose Attached-RTS, which includes PHY layer Attachment Coding and MAC layer AR-MAC, to fully utilize exposed terminals for concurrent transmissions. We implement Attachment Coding on GNU Radio testbed to verify its feasibility. We also conduct extensive simulations to evaluate the performance of Attached-RTS, which show that compared with 802.11 CSMA, Attached-RTS can achieve 200 percent improvement in exposed terminal configurations. By exploiting exposed terminal opportunities, Attached-RTS also achieves 180 percent performance gain in ad hoc networks.

In our current work, we simply rely on broadcasting to obtain neighborhood information in ad hoc networks. Although this is not our focus, we plan to leverage more sophisticated methods, such as ROME [23], to reduce the broadcasting overhead, eliminating the hidden actions, and increasing throughput efficiency.

The design of Attachment Coding establishes a new communication paradigm. In the next stage, we propose to exploit Attachment Coding to benefit more communication systems, such as cognitive radio networks and MIMO-based networks.

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