FAST: Realizing what your neighbors are doing

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***Abstract*—This paper presents the design, implementation, and evaluation of FAST (Full-duplex Attachment System), a cross layer system to solve both Hidden terminal problem and exposed terminal problems. The main reason that CSMA-like protocol cannot well solve hidden and exposed terminal problem both at once lies in the fact that they cannot obtain accurate Channel Usage Information (CUI, who is transmitting or receiving nearby) with low cost. FAST successfully obtains cost CUI in a cost-efficient way, thus can know exactly what are the neighborhood doing currently. FAST includes Attachment Coding in PHY layer to provide cost-effective CUI, and Attachment Sense in MAC layer to utilize CUI to identify hidden and exposed nodes in real time. Extensive simulation results show FAST can well solve both hidden and exposed terminal problems, and improves an average throughput to** 200% **over CSMA in practical ad-hoc networks.**

I. Introduction

Wireless technologies becomes more and more popular recently, resulting in a dense deployment of wireless devices. Therefore, it is desired to utilize concurrent transmission to improved the overall throughput in Wireless Local Area Networks(WLANs). However, concurrency can not be simply leveraged due to hidden terminal problem and exposed terminal problem [2] [6]. Extensive researches have been carried out to solve these two problems. Full duplex [3] allows receiver to send busy tune when receiving data packet. It mitigates hidden terminal problem, but exposed node still exists. CMAP [2] deduces exposed node by consulting to a "Conflict Map", but hidden terminal problem becomes severer. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) designs a handshake mechanism RTS/CTS [1] to mitigate both hidden and exposed terminal problems. However, RTS/CTS has rather high cost and introduces other problems like false blocking.

To solve hidden and exposed terminal problems together, we first have to cope with the tradeoff between collisions (hidden nodes) and unused capacities (exposed nodes). Carrier Sense (CS) is the best effort to resolve this tradeoff, but the information obtained (whether the channel is busy or not) is too coarse. We argue that accurate Channel Usage Information (CUI, which nodes are on transmissions or idle nearby) is required to resolve the above tradeoff. More specific, PHY layer techniques should be utilized to provide more knowledge about CUI. With accurate CUI, MAC layer protocol can be designed to guide node to make right access decision in the presence of hidden and exposed nodes.

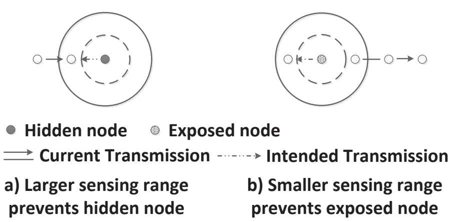

Fig. 1: An illustration of the tradeoff when using Carrier Sense

Interference Cancelation (IC) technique [6] [4] recovers transmission errors caused by interference, it also can be utilized for canceling intended jamming signals [5]. Inspired by IC, we propose a new coding scheme, Attachment Coding, to provide extra information we require without occupying the effective throughput for ongoing transmissions. Specifically, control information is modulated into interference-like signals called *Attachments*. By transmitting *Attachments* independently from data packets on air, neighbors are capable of acquiring control information as they need. Attachment Coding has the attractive feature to avoid additional bandwidth for control information, but it is not easy to be realized. First, how to efficiently modulate and encode *Attachments* remains concern. Second, receiver should be able to decode data packets when *Attachments* presence. Last, listeners who want control information should be able to acquire *Attachments* whenever they need.

Full duplex paradigm for wireless transceiver emerges based on IC, which inspires us to propose a cross layer FAST (Full-duplex Attachment System) to solve both hidden and exposed terminal problems. FAST contains a PHY layer protocol (Attachment Coding), which is applied on full duplex paradigm in Orthogonal Frequency Division Multiplexing (OFDM) based WLANs, and a MAC layer protocol (Attachment Sense), which utilizes the information provided by PHY layer to make access decision. Specifically, full duplex Attachment Coding let nodes modulates their IDs into *Attachments*, thus provides accurate CUI in real time. Accordingly, Attachment Sense can guide nodes to identify hidden and exposed nodes using CUI, and thus let them make right access decision fast and accurate.

To the best of our knowledge, FAST is the first work to tackle hidden and exposed terminal problems together in a cost-effective way. We evaluate FAST using NS3. Extensive

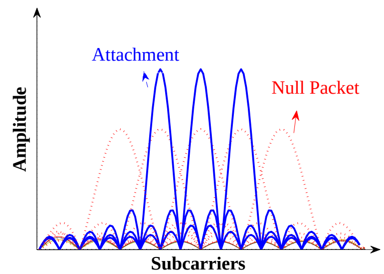

Fig. 2: An illustration of Attachment Coding to transmit control messages with/without data packets

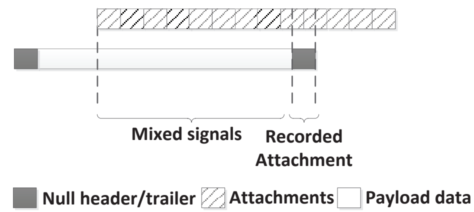

Fig. 3: Packet format and illustration for recording Attachments

simulation results shows that FAST can successfully resolve both hidden and exposed terminal problems, and improve the performance to 200% than CSMA in ad-hoc networks.

II. Attachment Coding

In this section, we describe the overall architecture in an Attachment Coding enabled communication system. Attachment Coding is built on top of OFDM based system, which modulates control information into narrow-band signals and transmit them into air. The design of Attachment Coding includes two components: (1) Attachment modulation and demodulation, and (2) Attachment cancelation and data recovery.

A. Attachment Modulation/Demodulation

We first talk about the basic idea of OFDM modulation. OFDM transforms a frequency-selective wide-band channel into a group of non-selective narrow-band channels named subcarriers. Accordingly, data stream is divided into several parallel bit streams, each modulated onto individual subcarrier.

In Attachment Coding design, each subcarrier carries one attached signal, which constitutes *Attachments*. In order 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 injects attached narrow-band signals into *Null Packets* and transmits them into air. *Null Packet* has exactly the same structure as normal packet, except that there is no information contained. As a payoff, the capacity of *Attachments* is small but acceptable, since *Attachments* for control information can be compressed simple and efficient. As describe in Sec. III-B, physical layer signaling with Binary Amplitude Modulation (BAM) can modulate *Attachments* into only one OFDM symbol, where one attached signal on a particular subcarrier can represent certain information. Moreover, in order to let node overhears *Attachments* whenever it needs in distributed networks, a *Cyclic Attachment* mechanism is proposed. Specifically, *Attachments* is repeated on every symbol within a *Null Packet*. Then no matter which time a node starts to monitor, the entire *Attachment* can be retained as long as it monitors more than one symbol duration. Even the *Attachment* is not captured exactly from the beginning, the missing portion can be retained from next symbol due to cyclic property.

For attachment receiver, 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 level and bursty feature. Therefore, when relatively high level energy is detected on a particular subcarrier, we can assume the presence of an attached signal.

B. Attachment Cancelation and Data Recovery

Since row signals at data receiver side may combine both *Attachments* and data packets, they can not be decoded directly. We leverage IC to cancel out attached signals on subcarriers. To record attached signals for cancelation, we encapsulate data packets with a null header and null trailer. These two symbols are called "null" for all subcarriers since ideally there is no signal except noise detected at data receiver side. According to [2], *Attachments* can be recorded on either null header or trailer when *Attachments* and data packets with comparable size superpose. Taking advantage of *Cyclic Attachment*, the recorded *Attachments* contain the entire attached signal waves across all the subcarriers. The recorded *Attachments* on null header or trailer can be expressed as:

$$y^{null}\left[t\right] = y_{attach}\left[t\right] + n\left[t\right] \tag{1}$$

Accordingly, the mixed signals in payload data with both data and attached signals can be expressed as:

$$y^{mixed}\left[t\right] = y_{\text{data}}\left[t\right] + y_{attach}\left[t\right] + n\left[t\right] \tag{2}$$

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

$$Data_i\left[t\right] = \frac{y_i^{mixed}\left[t\right] - y_i^{null}\left[t\right]}{H} \tag{3}$$

Fig.3 shows the packet format and the process of *Attachments* recording. After recording *Attachments*, receivers

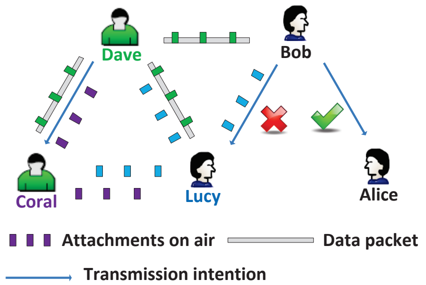

Fig. 4: Overview of Attachment Sense

utilize energy detection to distinguish whether a payload symbol need interference cancellation. If the symbol has a bursty energy distribution, cancellation is conducted to recover that symbol.

III. Attachment Sense

In this section, we present Attachment Sense, a MAC layer design that utilizes Attachment Coding on full duplex paradigm to solve both hidden and exposed terminal problems in distributed networks.

A. MAC Overview

The key insight to solve hidden and exposed terminal problems both at once stems from the phenomenon that, whether a transmission is successful and not only depends on channel condition near the receiver side. Therefore, we need receiver or victim (a node who is being affected by other transmissions) to claim that they are busy currently. With information that who is receiving or being affected within neighborhood, a sender is capable of avoiding transmitting to current receivers and victims (**hidden node**). Meanwhile, since a sender does not need to worry about other current senders nearby, it can also conduct concurrent transmissions when there is no receiver or victim presence (**exposed node**).

Inspired by the above observation, we propose Attachment Sense, which utilizes full duplex Attachment Coding to fulfill the above requirements. Specifically, sender, receiver and victim modulate their MAC addresses into *Attachments* and transmit them into air when they are on transmissions or being affected. These *Attachments* serve as the declaration of current unavailable nodes. Noted that sender is also required to transmit *Attachment* along with its data packets, to avoid performance deduction by busy sender (node wants to transmit to current sender). The design principle of Attachment Sense is simple and efficient, but there remain several implementation challenges. First, *Attachments* format should be designed efficiently due to limited bandwidth. Second, how to make access decision to resolve the tradeoff between hidden and exposed nodes remains concern. Last, when utilizing exposed nodes for transmissions, ACK collision with other data transmission has to be treated carefully.

B. Attachment Format

Attachment format should follow several principles. First, different nodes should have exclusive subcarriers for their *Attachments* to avoid confusion. However, accounting for limited subcarriers, it is difficult to allocate different subcarriers to different nodes in a decentralized manner. Second, it is impossible to modulate the whole MAC address due to high bandwidth cost. To address these problems, Attachment Sense has a specialized hash format, which contains the hash value of corresponding node's ID. Specifically, the whole subcarriers are split into sender, receiver and victim band. In each band, a membership vector of n subcarriers is used to represent node information. This hash format guarantees *Attachment* to be modulated into only one OFDM symbol (e.g. 256-point FFT). When a node transmits its *Attachment*, its MAC address is hashed into a value between $0-(n-1)$. Then the corresponding subcarriers in sender, receiver or victim band will carry a "1" bit. Since each node only needs to acquire the information within one-hop neighborhood (e.g. degree of 10). With a reasonably-sized n (e.g. 50), hash value collisions should be small enough.

C. Attachment Sense

Instead of carrier sense in CSMA, which detects carrier waves before transmitting, Attachment Sense simply asks node to listen to *Attachments* on air. The *Attachments* are generated as following: 1) Sender transmits data packets and *Attachment* simultaneously, 2) Receiver transmits *Attachment* once it starts to receive data packets, and 3) Victim transmits *Attachments* when it has been affected by other transmissions nearby.

To make channel access decision, each node maintains two distributed hash lists, Current Transmission List (CTL) and Neighborhood Hash List (NHL). CHL includes Current Sender Field (CSF), Current Receiver Field (CRF) and Current Victim Field (CVF). It is constructed whenever a node has packet to transmit. After a node detecting *Attachments* on air for one symbol duration, all the hash values contained in *Attachments* will be decoded and filled into CSF, CRF and CVF respectively. NHL simply encodes all one-hop neighbors' IDs. These IDs are also hash values to reduce overhead of NHL maintenance. Channel access decision is made as follows. When Bob is about to transmit to Alice (Alice has the hash value of $H(rev)$), he will firstly listen to *Attachments* on air. After obtaining CHL in hand, Bob will extract NHL and check the following metric:

$$((CRF \cup CVF) \notin NHL) \cap (H(rev) \notin CSF)$$

If this metric returns true, Bob can confirm his transmission and send packets to Alice. Otherwise, Bob have to defer his current transmission until the above metric is satisfied.

D. Points of Discussion

An issue to be discussed is whether Attachment Coding is compatible with full duplex paradigm. According to [3], full duplex is achieved by using *balun passive cancellation* at RX to cancel out self-interference from TX. This process will not be affected by Attachment Cancellation since Attachment

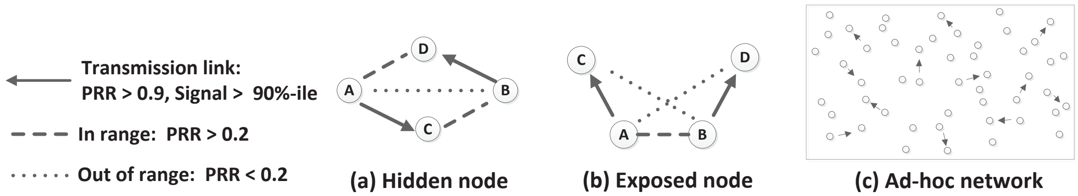

Fig. 5: Topologies overview, (a) (b) baseline topology in Sec. IV-A, and (c) practical networks in Sec. IV-B.

TABLE I: Configuration Parameters

Parameters	Values	Parameters	Values
SIFS	10μs	DIFS	32μs
Symbol time	32μs	Slot time	9μs
CW_{min}	16	CW_{max}	1024
Packet length	1460bytes	Basic data rate	6Mbps

Cancellation takes advantage of null header and trailer to cancel out the *Attachments* on air, which is completely independent from self-cancellation. Moreover, Attachment Coding supports full duplex transmission, where each node can double the throughput by sending while receiving. This lies in the fact that *Attachment* is transmitted independent from data, thus will not influence normal data transmission.

IV. Performance evaluation

In this section, we evaluate the performance of FAST through simulations using NS-3. As illustrated in Fig. 5, the simulation is divided into two parts: 1) Hidden node configuration and exposed node configuration, and 2) ad-hoc network configuration. The first configuration serves as baseline to see whether FAST can make the right access decision in particular scenarios. The second configuration evaluates FAST in practical networks with multiple sender-receiver pairs. For above simulation scenarios, channel bandwidth is 20Mbps with 256-point FFT OFDM modulation, where 192 and 8 subcarriers are used for data and ACK respectively. Detailed parameters are shown in Table I, following the specification of 802.11a. Each simulation lasts 50 seconds. The aggregate throughput is calculated at all the designated receivers. We compare FAST to 802.11 MAC with CS on and CS off.

A. Baseline Topology

In this part, the performance of FAST is evaluated with two sender-receiver pairs in two basic topologies, as shown in Fig. 5 (a) (b). We select the above three configurations from a general 50 nodes topology with random distribution and degree of 12 in Fig. 5 (d). Each configuration is repeated 50 times, with different sender-receiver pairs each time. The selection principles defined in Fig. 5 are trained in advance and recorded for each link.

1) Hidden node: Fig. 6 shows the performance in hidden node configuration. Ideally, there should only be one transmission at a time. CS on is unable to identify whether other nodes are receiving within neighborhood. Meanwhile, CS off merely transmits into air no matter there is any other receivers within transmission range. Thus nodes in CS on and off collide frequently, resulting a median throughout less than 3Mbps. Fortunately, backoff strategy mitigates performance deduction from collisions, and there are about 20% nodes achieving a throughput of 4Mbps. Conversely, FAST guides nodes to identify current receivers nearby (node C and D) through their *Attachments*, and thus prevents hidden nodes (node A and B) to transmit concurrently. Nodes transmit one after another, achieving a throughput of 5.2Mbps approximate to the ideal case for hidden node configuration.

2) Exposed node: Fig. 7 shows the performance in exposed node configuration. From the blue line with squares we can see that CS on prevents exposed node from transmitting concurrently. Thus most of the link pairs only achieve single-link throughout of 5Mbps. With CS off and ACK disabled, 27% of the link pairs achieve little more than single-link throughput, revealing that they are not actually exposed nodes. For the rest 73% of the link pairs, CS off leverages exposed nodes to achieve double-link throughput up to 10.5Mbps. FAST well traces the curve of CS off, indicating that through accurate CUI, Attachment Sense fully utilizes exposed nodes. Note that FAST has little performance deduction comparing with CS off (about 0.2 Mbps), since that ACK is disabled in CS off but FAST has ACK overhead to the overall throughput.

B. Practical Networks

In this part we quantify the performance of FAST in ad-hoc networks, as illustrated in Fig. 5(d). Hidden and exposed nodes significantly degrade the throughput of ad-hoc networks, especially with high node density and heavy traffic load [7]. We choose 6,8,10 and 12 number of concurrent senders as four configurations. Each configuration run 50 times, each time with different senders transmitting simultaneously with no more constraints.

Fig. 8 depicts the per-sender throughput for FAST, CS on and off in each configuration. By prevent hidden nodes from collisions and exploiting exposed nodes for concurrent transmissions, FAST improves per-sender throughput over CS on by between $180\%(N=6)$ and $200\%(N=8)$, and over CS off by between $200\%(N=6)$ and $220\%(N=8)$. When number of concurrent transmissions increases, nodes may transmit simultaneously and introduce unavoidable collisions, resulting in light performance degradation for FAST. However, it still improves the performance over CS by over

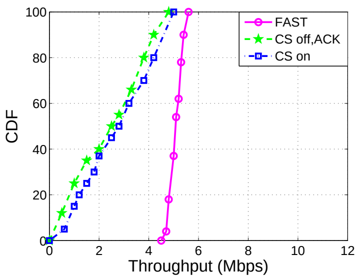

Fig. 6: Aggregate Throughput for Hidden Node Configuration

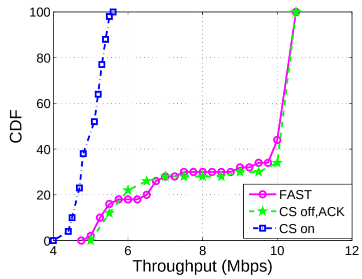

Fig. 7: Aggregate Throughput for Exposed node Configuration

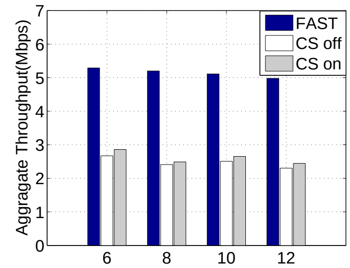

Fig. 8: Per-sender throughput in ad-hoc networks with different # of concurrent transmissions

200% (N=12). Thus, FAST is promising in dense networks and can achieve much better throughput over 802.11 CSMA.

V. Related Work

Hidden and exposed terminal problems have been long studied as they significantly degrade the performance in wireless networks [2] [6]. RTS/CTS based mechanism [1] tries to address these two problems using a RTS/CTS handshake. However, this mechanism is not feasible since it leads to considerable overhead. CMAP [2] proposes a "conflict Map" to deduce exposed nodes. A special header/trailer is designed for receivers to figure out interferers and thus allows exposed nodes to transmit concurrently. However, hidden terminal problem still exists. Full duplex [3] proposes a practical busy tune scheme to solve hidden terminal problem, but exposed terminal problem become severer. Unlike the above approaches, FAST well solves hidden and exposed terminal problems together with minimum cost.

Recently, PHY layer technique is desired to assist MAC layer protocol. In [8], PHY layer RTS/CTS is proposed for multi-round leader election. The novelty of Attachment Coding is that PHY control messages does not occupy the bandwidth of ordinal data traffic, thus significantly reduces control overhead. Side channel in [9] uses "interference pattern" for users to jam control information on other's data packets without IC, while FAST simply transmits control information on air, and recovers original data packets from row signals. Therefore, FAST is much flexible and reliable.

VI. Conclusion

In this paper, we propose a cross layer design FAST to solve both hidden and exposed terminal problems, which contains PHY layer Attachment Coding and MAC layer Attachment Sense. Attachment Coding transmits independent control information on air, saving the bandwidth for data traffic. Attachment Sense utilizes full duplex Attachment Coding to identify hidden and exposed nodes. Extensive simulation results show that compared with 802.11 CSMA, FAST can achieve 200% improvement, verifying that Attachment Coding provides cost-effective information for Attachment Sense to make access decision. In next stage, we propose to validate Attachment Coding on SDR platform [10], and exploit it to benefit more communication systems.

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