Combating Hidden and Exposed Terminal Problems in Wireless Networks

Lu Wang, *Student Member, IEEE,* Kaishun Wu, *Member, IEEE*, and Mounir Hamdi, *Fellow, IEEE*

***Abstract*—The hidden terminal problem is known to degrade the throughput of wireless networks due to collisions, while the exposed terminal problem results in poor performance by wasting valuable transmission opportunities. As a result, extensive research has been conducted to solve these two problems, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). However, CSMA-like protocols cannot solve both of these two problems at once. The fundamental reason lies in the fact that they cannot obtain accurate Channel Usage Information (CUI, who is transmitting or receiving nearby) with a low cost. To obtain additional CUI in a cost-efficient way, we propose a cross layer design, FAST (Full-duplex Attachment System). FAST contains a PHY layer *Attachment Coding*, which transmits control information independently on the air, without degrading the effective throughput of the original data traffic, and a MAC layer *Attachment Sense*, which utilizes the PHY layer control information to identify the hidden and exposed nodes in real time. We theoretically analyze the feasibility of the *Attachment Coding*, and then implement it on a GNU Radio testbed consisting of eight USRP2 nodes. We also conduct extensive simulations to evaluate the performance of FAST, and the experimental results show that FAST can effectively solve both the hidden and the exposed terminal problems, and improve the average throughput by up to 200% over CSMA in practical ad-hoc networks.**

***Index Terms*—Interference cancelation, wireless full-duplex, hidden terminal problem, exposed terminal problem.**

I. Introduction

The hidden and exposed terminal problems are two well-known problems in Wireless Local Area Networks (WLANs), which significantly degrade the network performance. As shown by [1], the hidden terminal problem introduces severe packet loss due to collisions for 10% of the sender-receiver pairs. Furthermore, in [2], the author shows that the exposed terminal problem can waste useful concurrent transmission opportunities. Extensive research has been carried out to solve these two problems. For example, full duplex [3] allows a receiver to send a busy tune when receiving a data packet. This scheme mitigates the hidden terminal problem, but the exposed node still exists. CMAP [2] deduces the exposed node and excludes a collided transmission by consulting a "Conflict Map", but the hidden terminal problem becomes even more acute. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) designs a handshake mechanism called RTS/CTS [4] to mitigate both the hidden and the exposed terminal problems. However, RTS/CTS induces a rather high cost and introduces other problems like false blocking. Therefore, RTS/CTS is disabled by default in WLANs.

When trying to solve both the hidden and the exposed terminal problems, a tradeoff arises 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 this tradeoff. More specifically, PHY layer techniques should be utilized to provide more information about CUI. Then MAC layer protocol can make the right channel access decision in the presence of hidden and exposed nodes.

Recently, Interference Cancelation (IC) [5] [6] has become a promising PHY layer technique to recover transmission errors caused by interference. This technique gives us an insight to propose a new coding scheme, *Attachment Coding*, to provide extra information we require without occupying the effective bandwidth for ongoing data transmissions. Specifically, control information is modulated into interference-like signals called *Attachments*. These *Attachments* can be attached to data transmission without reducing the decoding capacity of the data packets, since they can be easily canceled out at any receiver sides using Interference Cancellation. In this way, control information can be delivered without occupying any transmission time and bandwidth for data packets. By transmitting *Attachments* independently from the data packets on air, neighbors are able to acquire control information whenever they need, and leverage this information to make channel access decisions.

Attachment Coding has such attractive features to avoid additional bandwidth for transmitting control messages. However, this paradigm is not easy to be realized. We have encountered the following challenges. First, since the number of subcarriers is limited, how to efficiently modulate and encode *Attachments* remains a concern. Second, at the data receiver side , receivers should be able to decode data packets even when *Attachments* are present. Last, it is also important for listeners who want control information to acquire *Attachments*

Manuscript received May 5, 2012; revised July 12 and September 4, 2012; accepted September 5, 2012. The associate editor coordinating the review of this paper and approving it for publication was G. Bianchi.

L. Wang and M. Hamdi are with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong (e-mail: {wanglu, hamdi}@ust.hk).

K. Wu is with the HKUST Fok Ying Tung Graduate School, Hong Kong University of Science and Technology, Hong Kong. He is also with the National Engineering Research Center of Digital Life, State-Province Joint Laboratory of Digital Home Interactive Applications, Sun Yat-sen University, Guangzhou 510006, China (e-mail: kwinson@ust.hk).

Digital Object Identifier 10.1109/TWC.2012.092712.120628

whenever they need. These challenges need to be treated carefully to achieve an *Attachment Coding* paradigm and increase the whole system throughput.

Another emerging technique for wireless transceivers is a full duplex paradigm. This encourages us to propose a cross-layer design, FAST (Full-duplex Attachment System), to solve both the hidden and exposed terminal problems. FAST contains a PHY layer protocol, *Attachment Coding*, which is applied to a full duplex paradigm in Orthogonal Frequency Division Multiplexing (OFDM) based WLANs, and a MAC layer protocol, *Attachment Sense*, which utilizes the information provided by a PHY layer to make access decisions. Specifically, full duplex *Attachment Coding* provides accurate CUI in real time by letting transmitting nodes modulate their IDs into *Attachments*. Accordingly, *Attachment Sense* instructs nodes to identify hidden and exposed nodes through online CUI, and thus help them make the right access decisions.

We verify the feasibility of *Attachment Coding* using a GNU Radio testbed [7], and further evaluate the performance of FAST through a NS-3 network simulator. The experimental results in Sec. VI show that the *Attachment Coding* is feasible to transmit cost-effective control information. By utilizing *Attachment Coding*, FAST improves the performance by as much as 200% over CSMA in ad-hoc networks. The reason why we achieve these performance gains is that FAST can successfully identify and resolve both the hidden and exposed terminal problems. Therefore, interference introduced by hidden nodes can be reduced, and more concurrent transmissions that have not been carried out before due to exposed nodes can be leveraged now. To the best of our knowledge, FAST is the first research to tackle the hidden terminal problem and exposed terminal problem together in a cost-effective way.

In summary, the main contributions of this paper over existing protocols in distributed WLANs are as follows:

- We present a novel *Attachment Coding* scheme that enables nodes to transmit independent control messages on air, without degrading the performance of the original data transmission on a full duplex paradigm.
- We propose a new *Attachment Sense* scheme that builds on top of the new coding scheme, *Attachment Coding*, to solve both the hidden and exposed terminal problems and increase the network throughput.
- We theoretically analyze the feasibility of *Attachment Coding*, and implement real-time experiments using a GNU Radio Testbed for verification. We also conduct extensive simulations using NS-3 to evaluate the performance of the new communication system FAST. The results show that FAST achieves 200% better performance than CSMA in practical ad-hoc networks.

II. Related Works

A. Hidden and Exposed Terminal Problems

Researchers have devoted considerable amount of efforts on hidden and exposed terminal problems in wireless networks, since these two problems significantly degrade the network performance. The state-of art approach to solve both these two problems is to use an RTS/CTS handshake [4], which is also known as "virtual carrier sensing". RTS/CTS handshake utilizes RTS/CTS exchanges to avoid collision in case of a hidden terminal problem, and infers the transmission concurrency in case of an exposed terminal problem. Extensive mechanisms then emerge based on the RTS/CTS handshake. MACA-P [8] enhances the RTS/CTS mechanism to increase transmission concurrency. It designs a control gap to synchronize RTS/CTS exchange between different node-pairs. RTSS/CTSS [9] adds an off-line training phase before RTS/CTS exchanges to further explore transmission concurrency. However, the above RTS/CTS handshake based mechanisms are not feasible in practice, since RTS/CTS handshake leads to a considerable overhead. Full duplex [3] proposes a practical busy-tune scheme to solve the hidden terminal problem, but the exposed terminal problem become more severe. ZigZag decoding [1] utilizes interference cancellation to exploit asynchrony across successive collisions caused by hidden nodes. It can reduce the average packet loss rate at hidden terminals from 72.6% to about 0.7%. Also, exposed terminal problem has not been considered. Recent work named CMAP [2] proposes an on-line "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, the hidden terminal problem still exists. Unlike the above approaches, FAST utilizes a PHY layer technique to provide useful Channel Usage Information for higher layers. Therefore, it can solve both the hidden and exposed terminal problems in cost-efficient way.

B. PHY Layer Technique

PHY layer techniques have been frequently used to assist MAC layer protocols in recent years. In [10], a PHY layer RTS/CTS is proposed for multi-round leader election. A PHY layer interference model is proposed in [11] for link scheduling. In [12], the author utilizes a PHY layer ACK to reduce the overhead of traditional link layer ACK. Attachment Coding similarly shares the idea of PHY signaling, but differs from the above approaches in that it enables PHY layer control messages to be transmitted simultaneously with data traffic. Therefore, PHY layer control messages do not occupy the bandwidth of the original data traffic, and thus significantly reduces the control overhead. Side channel in [13] 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 the original data packets from row signals, which is much more reliable and flexible. Our previous work *h*jam [14] adds jamming signals on other users' packets, in this way they can provide access requests for a certain authority in centralized networks. Therefore, it cannot be used in decentralized networks. In FAST, however, control information is simply transmitted in *Attachments*, which is independent with ongoing data packets. Therefore, it can provide flexible PHY layer information for higher layer protocols, and is more suitable for distributed and unsynchronized networks.

III. Preliminary

We first introduce the basic idea of an OFDM based system. The OFDM modulation technique has been developed into

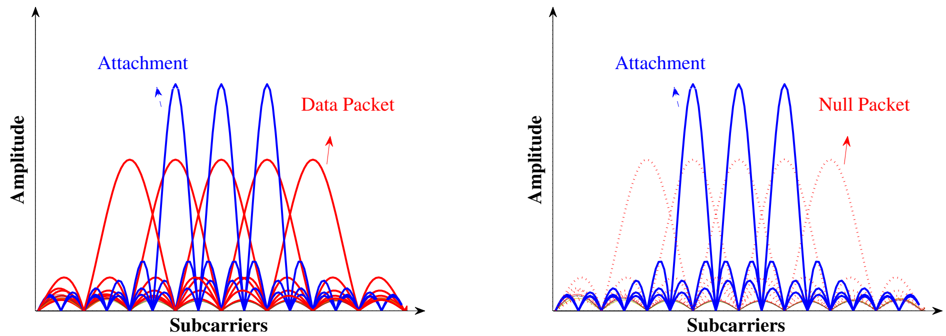

Fig. 1: An illustration of attachment coding to transmit control messages with data packets (left) and without data packets (right).

a promising technique for multi-carrier transmissions, which can improve the network performance significantly for future wireless communications. OFDM transforms a frequency-selective wide-band channel into a group of non-selective narrow-band channels named subcarriers, which makes it robust against large delay spreads and cross-talk effect by preserving orthogonality in the frequency domain.

On the transmitter side, the data to be transmitted on an OFDM signal is spread across the carriers of the signal, each carrier taking part of the payload. This baseband modulation is performed via an inverse Fast Fourier Transform (IFFT). To combat symbol misalignment (due to multipath effects), OFDM has a built-in robustness mechanism called Cyclic Prefix (CP). Instead of using an empty guard space, a cyclic extension of the OFDM symbol fills the gap. Then, the signal sequence with CP is converted into analogue signals and transmitted in the air.

Upon receiving the signals, the receivers sample the signals and pass them to a demodulation process chain. After a sampling procedure, the data sample blocks will be processed by an FFT process and the final result is the original data subject to certain scaling and phase rotations. These scaling and phase rotations are mainly due to channel dispersion. Therefore, channel equalization is needed to recover the original data from the distorted one.

IV. Attachment Coding

In this section, we describe the overall architecture of an *Attachment Coding* enabled communication system. *Attachment Coding* is built on top of an OFDM-based system. It modulates control information into narrow-band signals and transmits them into air without any impact on the original data packets. The design of *Attachment Coding* includes two components: (1) Attachment modulation and demodulation; and (2) Attachment cancelation and data recovery.

A. Attachment Modulation/Demodulation

In an Attachment Coding enabled system, each subcarrier carries one attached signal. These attached signals constitute *Attachments*. 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. 1 illustrates the main idea that injects attached narrow-band signals into data packets and *Null Packets*, and transmits them into air. A *Null Packet* has exactly the same structure as a 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 and be simple and efficient. As described in Sec. V-B, a physical layer signaling with Binary Amplitude Modulation (BAM) can modulate each *Attachment* into only one OFDM symbol, where one attached signal on a particular subcarrier can represent certain information. Moreover, in order to let a node overhears *Attachments* whenever it needs in distributed networks, a *Cyclic Attachment* mechanism is proposed. Specifically, each *Attachment* 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 of a symbol, the missing portion can be retained from the next symbol due to the cyclic property. This cyclic property ensures that listeners can obtain control information whenever they want.

At the attachment receiver side, it adopts an energy detection based method to detect an attached signal on a particular subcarrier. The detection principle lies in the fact that, high throughput transmissions and white noise spread their energy over the spectrum, while a narrow-band attached signal has relatively high energy level and is kind of bursty feature. Since an attached signal has a clear different distribution from a data signal and noise, when relatively high level energy is detected on a particular subcarrier, the attachment receiver can assume the presence of an attached signal. Although this method is simple, it is quite efficient, which can help an attachment receiver obtain an attached signal as soon as possible to interpret the corresponding control information as they need. We also notice that the detection algorithm also influences the detection accuracy and efficiency. We leave it to future research to find out more robust and efficient algorithms for *Attachment* detection.

B. Attachment Cancelation and Data Recovery

At the data receiver side, the row signals may combine both *Attachments* and data packets. Therefore, they cannot be decoded directly. IC is leveraged in our design to cancel out attached signals on each subcarrier. To record attached signals for the purpose of *Attachment* cancelation, each data packet is encapsulated with a null header and null tailer. These two symbols are called "null" since ideally there is no signal except noise detected at the data receiver side. According to [2], *Attachments* can be recorded on either header or tailer 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 *Attachment* on a null header or tailer can be expressed as:

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

The mixed signals in a payload data with both data and attached signals can be expressed as:

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

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 a 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 a data symbol. So the original data symbol after the *Attachment* cancelation can be expressed as:

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

After recording *Attachments*, receivers utilize energy detection to distinguish whether a payload symbol needs interference cancelation or not. If the symbol has a bursty energy distribution, cancelation is conducted to recover that symbol and obtain the original data information.

C. Theoretical analysis

To analyze the feasibility of Attachment Transmission in a theoretical way, we follow two principles: from a data receiver view, an attached signal cannot be too strong to corrupt the original data packet; from an *Attachments* receiver view, the signal strength of *Attachment* cannot be too weak to be "undetectable" in different subcarriers when multiple data packets superpose across the whole channel. Therefore, the signal strength of *Attachment* strikes a balance between these two principles.

1) Reliability of Data Transmission: The Signal to Interference Ratio at the Data Receiver side (SIRD) can be expressed as E_b/N_a, where E_b and N_a are power spectral density of OFDM symbol and attached signal respectively. We use Packet Reception Rate (PRR) to evaluate the quality of data transmission. As shown in Fig. 2, PRR has a direct connection with Bit Error Rate (BER), which is decided by the encoding/decoding scheme. Since an OFDM system applies a convolutional encoder as a channel coding scheme and a Viterbi hard decision decoder as a channel decoding scheme, we obtain an upper bound P_b on BER [15]:

TABLE I: Notations for BER calculation

k/n	number of information/coded bits in convolutional code
d/d_{free}	hamming distance/free hamming distance of the convolutional code
B_d	total number of information bit ones on all weight d paths
P_d	probability of selecting the incorrect path
ρ	ρ = W_a / W_s is ratio of the bandwidth of Attached signal W_a and OFDM symbol W_s

$$P_b=\frac{1}{k}\sum_{d=d_{free}}^{d_{free}+4}B_dP_d \tag{4}$$

P_d is calculated using Table I. When d is odd, P_d can be expressed as:

$$P_d=\sum_{i=\frac{d+1}{2}}^{d}\binom{d}{i}p^i(1-p)^{d-i} \tag{5}$$

and when d is even, P_d can be expressed as:

$$P_d=\frac{1}{2}\binom{d}{\frac{d}{2}}p^{\frac{d}{2}}(1-p)^{\frac{d}{2}}+\sum_{i=\frac{d+1}{2}}^{d}\binom{d}{i}p^i(1-p)^{d-i} \tag{6}$$

p can be considered as the coded BER in an AWGN (Additive white Gaussian noise) channel under an *Attachment* effect, with code rate $r={}^{k}/_{n}$. OFDM adopts a Binary Phase Shift Keying (BPSK) to modulate the preamble with convolutional encoding rate $1/2$, so we first use BPSK for illustration. Each attached signal increases the noise power spectral density from N_0 to N_0+N_a. Then BER for a coded OFDM subcarrier with *Attachment* is expressed as follows:

$$p=\rho\cdot Q\left(\sqrt{\frac{2rE_b}{N_0+N_a/\rho}}\right)+(1-\rho)\cdot Q\left(\sqrt{\frac{2rE_b}{N_0}}\right) \tag{7}$$

The computational results for Equation (4) are depicted in Fig. 2, which shows the relationship between PRR, BER, SIRD and SNR using different modulation schemes. It is noted that the typical working range of WLAN is from 20dB to 30dB for wireless networks [16]. With a reasonable number of *Attachments* as 10, BER is smaller than 10^{-7} with B/QPSK and 16 QAM, resulting in a PRR of 99.9%. Even with 64 QAM, we can achieve a PRR of 99.2%, which is sufficient for current 802.11 specifications. Therefore, Attachment Coding is nearly harmless to the original data transmission.

2) Feasibility of Attachment Transmission: We define the Signal to Interference Ratio at *Attachment* Receiver side (SIRA) as N_a/E_b. Then the received signal sample of an intended sender can be represented by:

$$\mathrm{y}\left(\mathrm{m}\right)=\sum_{i=1}^{n}\mathrm{h}_i\left(\mathrm{m}\right)\left[A_i\left(\mathrm{m}\right)+D_i(\mathrm{m})\right]+\mathrm{w}(\mathrm{m}) \tag{8}$$

where m denotes the sample index and $h_i(m)$ denotes the impulse response of the i^{th} channel. Without loss of generality, we assume the transmission channel is an AWGN channel, that is, $h_i(m)=h_0=1$. $A_i(m)$ and $D_i(m)$ are the attached signal and data signal of the ith channel, with zero-mean and variance of N_a and E_b respectively. $w(m)$ denotes a complex Gaussian Noise with zero-mean and variance of N_0. According to [17] , the probability of missing an *Attachment* when one is present on a certain subcarrier P_{miss} is:

$$P_{miss}(\lambda) = Pr(\frac{1}{M}\sum_{m=1}^{M}|\mathrm{y}\,(\mathrm{m})|^2 < \lambda) \quad (9)$$

where M is the number of samples and N is the maximum number of neighbors among a node. The threshold level for energy detection, λ, should be at least larger than $N \cdot E_b$, so that the attached signal can be detected using an energy detection mechanism. The computational results for Equation (9) are depicted in Fig. 3 to see the probability of miss detection P_{miss} under different SIRA and SNR. Generally, P_{miss} is acceptable in a typical wireless working range, with values below 10^{-25}. Therefore, we can conclude that the signal strength of an *Attachment* cannot to be too much larger than the signal strength of a data symbol (e.g. 3 times). In this way we can both ensure the performance of data transmission and attachment detection.

V. Attachment Sense

In this section we will present the design of Attachment Sense. Attachment Sense is a MAC layer protocol that utilizes Attachment Coding on a full duplex paradigm to solve both the hidden and exposed terminal problems in distributed networks. In this section, we first present an overview of Attachment Sense along with the design challenges. Detailed modules of Attachment Sense are then given to see how we address these challenges. Some points of discussions which are related to our design will be demonstrated at the end of this section.

A. MAC Overview

The key insight to solve the hidden and the exposed terminal problems both at once stems from the phenomenon that, whether a transmission is successful or not depends only on the channel condition near the receiver side. Therefore, we need a receiver or a victim (a node who is being affected by other transmissions) to claim that they are currently busy within this neighborhood. With the information that who is receiving or being affected nearby, a sender is capable of deferring the transmission to them (**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 presences (**exposed node**). With this transmission status (CUI) in hand, the hidden and the exposed terminal problems can be both solved.

Inspired by the above observation, we propose an Attachment Sense, which utilizes full duplex Attachment Coding to fulfill the above requirements. Specifically, a sender, a receiver and a victim modulate their identities into *Attachments* and transmit them into the air when they are on transmissions or being affected. These *Attachments* serve as a declaration of current "unavailable" nodes. It is noted that a sender is also required to transmit an *Attachment* along with its data packets. This is to avoid performance degradation by a busy sender (a sender who is transmitting now is also the receiver of other senders). The design principle of Attachment Sense is simple and efficient, but there remain several implementation challenges. First, an *Attachment* format should be designed efficiently due to the limited bandwidth of each subcarrier. Second, how to make an access decision to resolve the tradeoff between the hidden and exposed nodes remains a concern. Last, when utilizing exposed nodes for concurrent transmissions, we should carefully cope with ACK collision with other data transmissions to increase the Packet Reception Rate.

B. Attachment Format

The format of *Attachments* should follow several principles. First, different nodes should have exclusive subcarriers for their *Attachments* to avoid confusion. However, since the number of subcarriers is limited, it is not easy to allocate different subcarriers to different nodes in a decentralized manner. Second, it is impossible to modulate the whole identity (MAC address) into *Attachments* due to high bandwidth cost. To address these problems, Attachment Sense has a specialized hash format, which contains the hash value of the corresponding node's ID. Specifically, the whole subcarriers are split into a sender, a receiver and a victim band. In each band, a membership vector of n subcarriers is used to represent a node identity. This hash format guarantees that an *Attachment* is 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 to $(n-1)$. Then the corresponding subcarrier in a sender, a receiver or a victim band will carry a "1" bit. Each node only needs to acquire the information of the channel usage within one-hop neighborhood (e.g., a degree of 15 in a sparse to medium network [18], where each node has no more than 15 neighbors nearby). With a reasonably-sized n (e.g., 50), a hash value collisions should be small enough.

C. Attachment Sense

Unlike CSMA that detects carrier waves before transmitting, Attachment Sense simply asks a node to listen to *Attachments* on air. The *Attachments* are generated according to the following rules: 1) The sender transmits data packets and *Attachments* simultaneously; 2) The receiver transmits *Attachments* once it starts to receive data packets; and 3) The victim transmits *Attachments* when it has been affected by other transmissions nearby.

To make a channel access decision, each node maintains two distributed hash lists, Current Transmission List (CTL) and Neighborhood Hash List (NHL). CTL includes the Current Sender Field (CSF), the Current Receiver Field (CRF) and the Current Victim Field (CVF). It is constructed whenever a node has a 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 the one-hop neighbors' IDs. These IDs are also designed as hash values to reduce the overhead of NHL maintenance.

We illustrate how to make a channel access decision using Fig. 4 through an example. As shown in the figure, Dave is transmitting packets to Coral. The *Attachments* from both Dave and Coral indicate that they are the current sender and

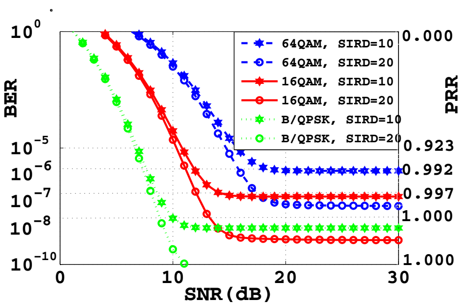

Fig. 2: Relationship between BER, PRR, SIRD, SNR with different modulation schemes (# of *Attachments* = 10, Packet length = 1000 byte).

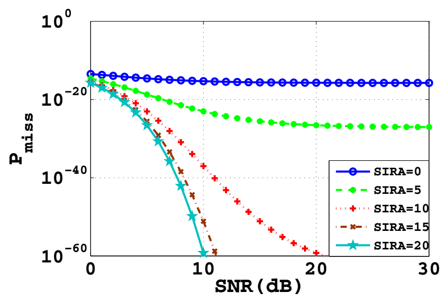

Fig. 3: Probability of missing an attached signal under different SNR and SIRA conditions.

receiver respectively. Meanwhile, Lucy is being affected by Dave's packets, so she also transmits *Attachments* to declare she is currently a victim. When Bob has a packet to transmit to Alice or Lucy (who has the hash value of $H(rev)$), he will first listen to *Attachments* on air and obtain CTL in hand, including Dave in CSF, Coral in CRF and Lucy in CVF. After that, Bob will extract the NHL from his routing table, which consists of Dave, Lucy and Alice. To make the channel access decision that whether he can transmit to Alice or not, he will check the following metric:

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

where $(CRF \notin NHL)$ indicates there are no current receivers within neighborhood. And $(H(rev) \notin (CSF \cup CVF))$ indicates the intended receiver is capable of receiving packets, since he is neither a sender nor a victim at that moment. This metric aims to meet all the transmission conditions. If Bob wants to transmit to Alice, the above metric will return true, since there are no other receivers nearby, and the intended receiver Alice is neither a sender nor a victim. Therefore, Bob can confirm his transmission and send packets to Alice immediately. Otherwise, if Bob wants to transmit to Lucy, this metric will return false. Although there is no other receivers nearby, his intended receiver Lucy is not able to receive packets. So Bob has to defer his transmission and keeps listening to *Attachments* until the above metric is satisfied. In this way, both hidden and exposed terminal problems can be avoided.

D. Points of Discussion

We finish the description of FAST with a few discussion points. For the issues we talk about below, we broadly describe the potential approaches to cope with them. Nevertheless, it leaves exhaustive discussions in further research.

The first issue is to resolve collisions among different kinds of transmissions. First, ACK may collide with data packets when utilizing exposed nodes for concurrent transmissions within a neighborhood. To avoid ACK collision with data packets, we split a small portion of the subcarriers from the whole channel, which are only used for an ACK transmission. In this case ACK transmission can be separated from data transmission. Second, collisions may also happen when two senders transmit almost simultaneously. To avoid further

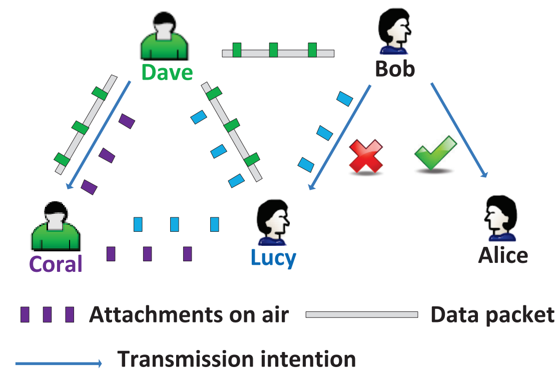

Fig. 4: Overview of attachment sense.

collision caused by simultaneous transmissions, a backoff counter and a small backoff window is adopted. When a sender notices a collision took place, it will increase the counter by 1, otherwise, the counter is set to 0. Whenever the counter exceeds a certain threshold, say 3, the sender will backoff for a few time slots.

A second issue to be discussed is whether Attachment Coding is compatible with a full duplex paradigm. According to [3], full duplex is achieved by using *balun passive cancelation* at RX to cancel out self-interference from TX. This process will not be affected by Attachment Cancelation since Attachment Cancelation takes advantage of the null header and tailer to cancel out the *Attachments* on air, which is completely independent from self-cancelation. Moreover, Attachment Coding supports full duplex transmission, where each node can double the throughput by sending while receiving. This lies in the fact that an *Attachment* is transmitted independent from data, and thus will not influence normal data transmission.

The third issue is to analyze whether a hash value collision will introduce some performance degradation. Since FAST uses hash values to represent nodes' IDs, different nodes may have the same hash value within a neighborhood. In this case, they cannot be distinguished by other nodes. We define that in FAST, whenever a sender detects a hash value collision, it will always defer the current transmission. This conservative manner successfully avoids data packet collisions and reduces the performance loss. To analyze the actual performance loss due to hash collisions, we use a pair-collision for illustration. Pair-collision can be divided into two cases, as shown in

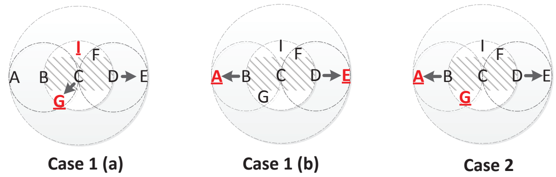

Fig. 5: Illustration of hash value collision.

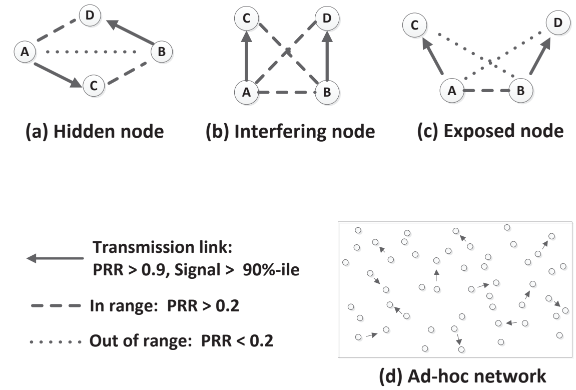

Fig. 6: Topologies overview, (a) (b) (c) baseline topology in Sec. VI-B1, and d) practical networks in Sec. VI-B2.

Fig. 5: collision within the same-hop (e.g. $H(I) = H(G)$ or $H(A) = H(E)$), and collision between different hops (e.g. $H(A) = H(G)$). In case 1, a hash collision results in the same action (defer transmission in Case 1(a), or conducts transmission in Case 1(b)), and thus does not introduce a performance loss. In Case 2, since C is not able to distinguish A from G, deferring transmission wastes exposed terminal opportunity. This probability of performance loss can be derived using a geometry representation. We define the entire two-hop area to be unit 1. As a numerical example, we assume that 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, P_{lost} should satisfy the following conditions:

- A is receiving a data packet in the white area. This probability can be expressed as: $P(A) = \frac{3}{4} \times \frac{1}{3}$, where $\frac{3}{4}$ represents that A is in the white area, and $\frac{1}{3}$ represents that A is a receiver;
- G is idle in the shadow area and out of the communication range of the current sender D. This probability can be expressed as: $P(G) = \frac{1}{4} \times \frac{2}{3} \times \frac{1}{3}$, where$\frac{1}{4} \times \frac{2}{3}$ represents that G is in the shadow area and out of the communication range of D, and $\frac{1}{3}$ represents that G is idle currently.

Then the probability of missing a concurrent transmission opportunity, $P_{Lost} = P(A) \times P(G) = \frac{1}{72}$, which is relatively small. More number of hash collisions (e.g. triple-collision) can be proven using similar methodology, which has even a smaller probability to introduce a performance loss. Therefore, hash collisions can be harmless.

VI. Performance Evaluation

In this section, we first present the performance evaluation of Attachment Coding using our prototype implementation, which is built on a GNU radio testbed in an indoor environment. Then NS-3 is utilized to study the performance of FAST over 802.11 standards under various topologies. Our experimental results show that Attachment Coding can work quite well. In addition, it does not have much impact on the original data transmission. Our simulation results show that, comparing with the 802.11 CSMA, FAST achieves up to 200% performance gain under dense-deployed ad-hoc networks.

A. *Feasibility of Attachment Coding*

In this part, we will conduct real-time experiments on GNU radio testbed to evaluate the feasibility of Attachment Coding. The feasibility evaluation follows two questions: 1) whether data transmission can be reliably decoded in the presence of Attachment Transmission, and 2) whether we can successfully detect Attachment Transmission and obtain the control information from it. These two questions are consistent with our theoretical analysis in Sec. IV-C. To find out the answer to the above two questions, we conduct the following hardware experiments.

System Implementation: We first describe the implementation of our testbed. We utilize a GNU radio testbed for our experiments, and implement Attachment Coding using a Software Defined Radios (SDRs). The Universal Software Radio Peripheral 2 (USRP2) works as an RF frontend. Our testbed consists of 8 USRP2 nodes with RFX2400 daughterboards operating in the 802.11 frequency range of 802.11 standards. Unless otherwise specified below, we use the default configuration as shown in Table. II. Specifically, we use a bandwidth of around 2MHz and split it into 52 subcarriers. These changes are made since we want to make the inter subcarrier spacing comparable to 802.11 (0.3125MHz) while still maintaining the normal transmission of USRP2, which is limited by the hardware itself. We also make SIFS and DIFS longer to ensure that during attachment sense, a sender can overhear a whole OFDM symbol [7]. All of our experiments run on the 2.425GHz, and BPSK is used as the modulation scheme. We still follow the two principles discussed in the previous subsection as the principles for evaluation.

Reliability of Data Transmission: To evaluate the reliability of data transmission under the impact of Attachment Transmission, we first 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. The data receiver is in the transmission range of both data sender and attachment sender. We let the data sender transmit normal packets to the data receiver, and simultaneously let the attachment sender transmit *Attachments* to the attachment receiver. We compute the PRR(Packet Reception Rate) at a data receiver side under various SNRs, first without jamming, and then with jamming. Each run transfers 2500 packets, and for each value of SNR, the experiment is repeated 10 times.

The PRR of a data receiver with and without Attachment Transmission is plotted in Fig. 7. The x-axis is the received SNR at the data sender side, which is ranging from 4dB to 20dB. As SNR is around 5dB, the PRR is quite small for both cases (with/without Attachment Transmission). However, when SNR is greater than, say 10dB, there is almost no perfor-

TABLE II: 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

mance degradation with Attachment Transmission, comparing with the performance of data transmission without Attachment transmission. Since the typical working range of an SNR region for 802.11 is 10-30dB [19], the impact of Attachment transmission is acceptable. Therefore, these results verify that Attachment Transmission do not have much influence on data transmission. It is noticed that these experimental results are not as good as theoretical analysis in Sec. IV-C. This stems from two reasons. First, USRP has certain limitations in strict timing and accurate sampling due to software-defined signal processing. Second, our implementation runs in a public user-space in the unlicensed 2.4GHz range. Therefore, external interferences are unavoidable.

After that, we conduct another experiment to see whether the number of concurrent Attachment Transmissions will influence the decodability of the data receiver. The experiment uses 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 also calculate the Packet Loss Rate (PLR) under different number of Attachment Transmissions for two cases, SNR equals to 10dB and 15dB. The results show that a lower SNR has relatively higher PLR. However, even for SNR = 10dB, the PLRs are under 10^{-2}, which are quite small and acceptable. According to the theoretical analysis in Sec. IV-C, the performance loss is expected to increase as the number of concurrent Attachment Transmissions increases. However, the experimental results show that the performance loss varies randomly under different number of concurrent Attachment Transmissions. This observation shows that practical results are different from the theoretical results, and the difference may be due to the processing capability of the USRP2 hardware.

Feasibility of Attachment Transmission: To evaluate the performance of Attachment Transmission, we measure the detection accuracy at the attachment receiver side. The detection accuracy is affected by two parameters: Miss Detection Rate (P_{miss}) and False Alarm Rate (P_{false}), both of which will result in a 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 an attachment sender keep transmitting *Attachments* in the presence of data transmission, and then PRR is computed under various values of SNRs of the *Attachments* signal ranging from 8dB to 20dB. Each run transfers 2500 packets, and for each value of SNR, the experiment is repeated 10 times.

According to the theoretical analysis in Sec. IV-C, we expect that the P_{false} to be very small. From the experimental results we find out that there is almost no P_{false} for all runs, which is consistent with the theoretical analysis. The results of P_{miss} show that when SNR is greater than a certain threshold, e.g., 12dB, we can achieve a very small P_{miss} of less than 1%. Therefore, the corresponding detection accuracy is more than 99%. Therefore, Attachment Transmission can also be detected accurately, which verifies its feasibility.

B. Performance of FAST

Due to the latency constraint of USRP2, we are not able to conduct real-time evaluation of FAST for system throughout. Therefore, in this section, we conduct extensive simulations to evaluate the performance of FAST using network simulator NS-3. As illustrated in Fig. 6, the simulations are divided into two parts: 1) baseline topology, including hidden nodes, interfering nodes and exposed nodes configuration, and 2) practical networks, which is ad-hoc network configuration. The first configuration serves as a baseline to see whether FAST can make the right access decisions in particular scenarios. The second configuration evaluates FAST in practical networks with multiple sender-receiver pairs. For the above simulation scenarios, channel bandwidth is 20 Mbps with 256-point FFT OFDM modulation, where 192 and 8 subcarriers are used for data and ACK respectively. Detailed parameters are shown in Table II, 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* ("ideal case" for an interfering node) and *CS off* ("ideal case" for an exposed node).

1) Baseline Topology: In this part, the performance of FAST is evaluated with two sender-receiver pairs in three basic topologies, as shown in Fig. 6 (a) (b) (c). We select the above three configurations from a general 50-node topology with random distribution and degree of 12 (average number of neighbors) in Fig. 6 (d). Each configuration is repeated 50 times, with different sender-receiver pairs each time. The selection principles are shown in Fig. 6, which are trained in advance and recorded for each link.

Hidden node Fig. 8 shows the performance of *CS on*, *CS off* and FAST in a hidden node configuration. Ideally, there should only be one transmission at a time. *CS on* is unable to identify whether other nodes are receiving data packets within a neighborhood. Meanwhile, *CS off* merely transmits into air no matter there is any other receiver within a transmission range. Therefore, nodes in *CS on* and *CS off* collide frequently, resulting in a median throughout of less than 3 Mbps. Fortunately, a backoff strategy mitigates the performance degradation from collisions, and there are about 20% nodes achieving a throughput of 4 Mbps. In the other hand, FAST instructs 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. In this case, nodes transmit one after another, and can achieve a throughput of 5.2 Mbps , which approximates the ideal performance for a hidden node configuration.

Interfering node Fig. 9 shows the performance of *CS on*, *CS off* and FAST in an exposed node configuration. *CS off* achieves zero throughput for over 40% of the link pairs, where concurrent transmissions are completely corrupted by each

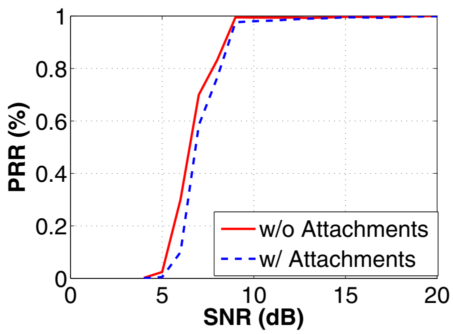

Fig. 7: Decodability of data transmission with/without attachment transmission under different SNRs.

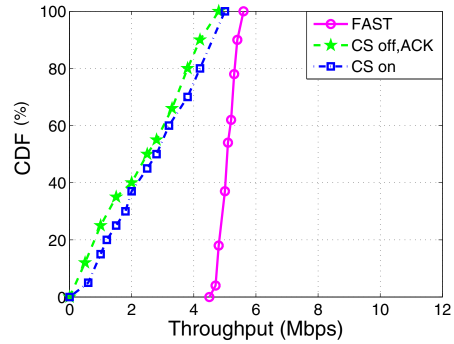

Fig. 8: Aggregate throughput for hidden node configuration.

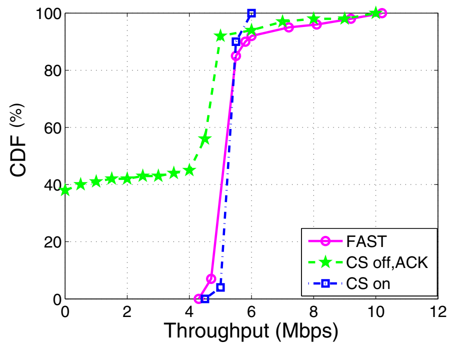

Fig. 9: Aggregate throughput for interfering node configuration.

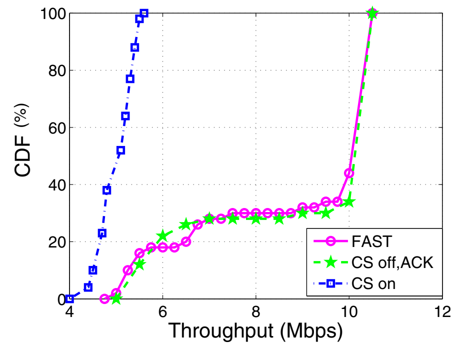

Fig. 10: Aggregate throughput for exposed node configuration.

other. For the rest 60% of the link pairs, interfering simultaneous transmissions give *CS off* very poor performance. In the contrary, FAST correctly figures out interfering transmissions through *Attachments* from victims, and let senders take turns to transmit. In this case, FAST can achieve almost a single-link throughout as *CS on*. There are 8% of the link pairs achieve double-link throughput for *CS off* (on top of the figure), indicating that they are actually exposed nodes. For these link pairs, FAST quickly traces the curve of *CS off* and achieves a similar performance.

Exposed node Fig. 10 shows the performance of *CS on*, *CS off* and FAST in an exposed node configuration. From the dash-dot line with squares we can see that *CS on* prevents exposed nodes from transmitting concurrently. Thus most of the link pairs only achieve single-link throughout of 5 Mbps. 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 10.5 Mbps. FAST traces well the curve of *CS off*, indicating that through accurate CUI, Attachment Sense fully utilizes exposed nodes. It is noted that FAST has little performance reduction comparing with *CS off* (about 0.2 Mbps), for the reason that ACK is disabled in *CS off*, but FAST still has ACK overhead to the overall throughput.

2) Practical Networks: In this part, we quantify the performance of FAST in ad-hoc networks [20] [21], as illustrated in Fig. 6 (d). In ad-hoc networks, hidden and exposed nodes significantly degrade the network performance, especially with high node density and heavy traffic load [22]. We choose 6, 8, 10 and 12 number of concurrent senders as four configurations. Each configuration run 50 times, and each time with different senders transmitting simultaneously with no more constraints.

We calculate the per-sender throughput for FAST, *CS on* and *CS off* in each configuration. By preventing 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 the number of concurrent transmissions increases, nodes may transmit simultaneously and introduce unavoidable collisions, resulting in small performance degradation for FAST. However, it still improves the performance over *CS* by over 200% (N=12). Therefore, FAST is promising in dense networks and can achieve much better throughput over 802.11 CSMA.

VII. Conclusion

In this paper, a cross-layer design, FAST, is proposed to solve both the hidden and the exposed terminal problems in distributed wireless networks. FAST consists of two components, a PHY layer Attachment Coding and a 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 in real-time, and thus can solve both the hidden and exposed terminal problems. Experimental results demonstrate the feasibility of Attachment Coding. Extensive simulation results show that compared with 802.11 CSMA, FAST can achieve 200% improvement in distributed networks, verifying that FAST can successfully solve the hidden and exposed terminal problems in a cost-effective way. In the next stage, we propose to exploit Attachment Coding to benefit more communication systems, like cognitive radio networks [23] and MIMO based networks [24].

Acknowledgment

This research is supported in part by HKUST Grant RPC10EG21, 2012 Guangzhou Pearl River New Star Technology Training Project (No.2012J2200081), China NSFC Grant 61202454. Kaishun Wu is the corresponding author.

References

[1] S. Gollakota and D. Katabi, "Zigzag decoding: combating hidden terminals in wireless networks," *ACM SIGCOMM Computer Commun. Rev.*, vol. 38, no. 4, 2008.

[2] M. Vutukuru, K. Jamieson, and H. Balakrishnan, "Harnessing exposed terminals in wireless networks," in *Proc. 2008 USENIX Symposium on Networked Systems Design and Implementation*.

[3] M. Jain, J. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *2011 ACM MobiCom*.

[4] I. W. Group *et al.*, IEEE 802.11-2007: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 2007.

[5] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: analog network coding," *ACM SIGCOMM Computer Commun. Rev.*, vol. 37, no. 4, 2007.

[6] K. Wu, H. Tan, H. Ngan, and L. Ni, "Chip error pattern analysis in IEEE 802.15. 4," in *2010 IEEE INFOCOM*.

[7] K. Tan, J. Fang, Y. Zhang, S. Chen, L. Shi, J. Zhang, and Y. Zhang, "Fine-grained channel access in wireless LAN," in *ACM SIGCOMM Computer Commun. Rev.*, vol. 40, no. 4, 2010.

[8] A. Acharya, A. Misra, and S. Bansal, "Design and analysis of a cooperative medium access scheme for wireless mesh networks," in *2004 IEEE International Conference on Broadband Networks*.

[9] K. Mittal and E. Belding, "RTSS/CTSS: mitigation of exposed terminals in static 802.11-based mesh networks," in *2006 IEEE Workshop on Wireless Mesh Networks*.

[10] B. Roman, F. Stajano, I. Wassell, and D. Cottingham, "Multi-carrier burst contention (MCBC): scalable medium access control for wireless networks," in *2008 IEEE Wireless Communications and Networking Conference*.

[11] P. Wan, O. Frieder, X. Jia, F. Yao, X. Xu, and S. Tang, "Wireless link scheduling under physical interference model," in *2011 IEEE INFOCOM*.

[12] A. Dutta, D. Saha, D. Grunwald, and D. Sicker, "Smack: a smart acknowledgment scheme for broadcast messages in wireless networks," in *ACM SIGCOMM Computer Commun. Rev.*, vol. 39, 2009.

[13] K. Wu, H. Tan, Y. Liu, J. Zhang, Q. Zhang, and L. Ni, "Side channel: bits over interference," in *2010 ACM MobiCom*.

[14] K. Wu, H. Li, L. Wang, Y. Yi, Y. Liu, Q. Zhang, and L. Ni, "HJAM: attachment transmission in WLANS," in *Proc. 2012 IEEE INFOCOM*.

[15] J. Proakis, *Digital Communications*. McGraw-Hill, 1987.

[16] M. Souryal, L. Klein-Berndt, L. Miller, and N. Moayeri, "Link assessment in an indoor 802.11 network," in *2006 IEEE Wireless Communications and Networking Conference*, vol. 3.

[17] Y. Lee and D. Oh, "Energy detection based spectrum sensing for sensing error minimization in cognitive radio networks," *International J. Commun. Networks and Inf. Security*, vol. 1, no. 1, 2011.

[18] X. Feng, J. Zhang, Q. Zhang, and B. Li, "Use your frequency wisely: explore frequency domain for channel contention and ACK," in *Proc. 2012 IEEE INFOCOM*.

[19] M. Souryal, L. Klein-Berndt, L. Miller, and N. Moayeri, "Link assessment in an indoor 802.11 network," in *Proc. 2006 IEEE Wireless Communications and Networking Conference*, vol. 3.

[20] W. Yu, J. Cao, X. Zhou, and X. Wang, "A high-throughput MAC protocol for wireless ad hoc networks," in *2006 IEEE International Conference on Pervasive Computing and Communications Workshops*.

[21] M. Dianati, X. Ling, K. Naik, and X. Shen, "Performance analysis of the node cooperative ARQ scheme for wireless ad-hoc networks," in *Proc. 2005 IEEE GLOBECOM*, vol. 5.

[22] S. Zhao, L. Fu, X. Wang, and Q. Zhang, "Fundamental relationship between nodedensity and delay in wireless ad hoc networks with unreliable links," in *2011 ACM MobiCom*.

[23] N. Zhang, N. Lu, R. Lu, J. Mark, and X. Shen, "Energy-efficient and trust-aware cooperation in cognitive radio networks," in *2012 IEEE ICC*.

[24] L. Fu, Y. Zhang, and J. Huang, "Energy efficient transmissions in MIMO cognitive radio networks," in *2012 IEEE Conference on Information Sciences and Systems*.

Lu Wang received her B.Eng. degree from Nankai University, Tianjin, in 2009, and is currently working towards the PHD degree in computer science and engineering in Hong Kong University of Science and University. Her research interests focus on wireless communications, including ad hoc networks and cognitive radio networks.

Kaishun Wu is currently a research assistant professor in Fok Ying Tung Graduate School with the Hong Kong University of Science and Technology. He received the Ph.D. degree in computer science and engineering from Hong Kong University of Science and Technology in 2011. Before his Ph.D. career, he received his B.Eng. degree from Sun Yat-sen University in 2007. His research interests include wireless communication, mobile computing, wireless sensor networks and data center networks.

Mounir Hamdi received the B.S. degree in Electrical Engineering - Computer Engineering minor (with distinction) from the University of Louisiana in 1985, and the MS and the PhD degrees in Electrical Engineering from the University of Pittsburgh in 1987 and 1991, respectively. He is a Chair Professor at the Hong Kong University of Science and Technology, and the Head of the Department of Computer Science and Engineering. He is an IEEE Fellow for contributions to design and analysis of high-speed packet switching.