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Load Adaptive MAC: A Hybrid MAC Protocol for MIMO SDR MANETs

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Abstract—The performance of prevalent wireless MAC protocols is a function of network contention level and the capabilities of the underlying network nodes. While contention-based MAC protocols such as CSMA experience significant performance degradation under high contention levels, slot-based MAC protocols such as TDMA perform in the opposite way. In this paper, we propose a hybrid MAC protocol to which we refer as Load-Adaptive MAC (LA-MAC) protocol for MANETs formed by a collection of Multiple-Input Multiple-Output (MIMO) equipped nodes. By adaptively switching its mode of operation between CSMA and TDMA, LA-MAC achieves a high channel utilization and a reasonable delay profile under both high and low contention levels identified by the measured collision rate of the MAC frames. As a cross-layer protocol, LA-MAC relies on the information received from the physical layer in order to distinguish between corrupted frames due to actual collisions as opposed to those corrupted by wireless link effects such as fading. We describe the design of LA-MAC protocol and report on its implementation in a MANET testbed formed by a collection of MIMO Universal Software Radio Peripheral (USRP) Software Defined Radio (SDR) nodes. Through analytical and experimental studies, we compare the performance of LA-MAC with that of CSMA and TDMA under different traffic conditions. The results show the improvements achieved by LA-MAC in comparison with other alternatives.

Index Terms—SDR, USRP, GNU radio, MANET, MIMO, CSMA, TDMA, hybrid MAC.

I. INTRODUCTION

O VER the past few years, a spectrum of wireless MAC protocols, ranging from contention-based to slot-based protocols, have been proposed. With no reliance on any topology or synchrony information, contention-based protocols such as Carrier Sense Multiple Access (CSMA) [1]–[3] are typically robust to topology changes. However and as analyzed by [4], the performance of CSMA protocols is degraded under high contention regimes due to collisions. In contrast, slot-based protocols such as Time Division Multiple Access (TDMA) [5], [6] utilize synchrony among neighboring nodes to achieve collision-free transmission by assigning transmission time slots to individual nodes. While slot-based protocols can generally achieve high channel utilization under high contention regimes as they cannot fully utilize the

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transmission medium. Further, the loss of synchrony due to factors such as time varying nature of wireless channel, clock synchronization overhead [7], and interference irregularity [8] problems can negatively impact the performance of slot-based protocols. Accordingly, the primary motivation of this work is to dynamically trade off the advantages and disadvantages of CSMA and TDMA.

In what follows a review of the literature in a close context to the problem space of this paper is provided. Adapting a hybrid behavior between TDMA and CSMA according to the level of contention was first explored in [9]. DRAND [10] is a relatively scalable channel scheduling algorithm that can be used to assign time slots to network nodes. B-MAC [2] is a low power MAC protocol designed for sensor networks. Utilizing the work of [9], [10], and [2], Z-MAC [11] was proposed as another hybrid MAC protocol for sensor networks. One observation is that the protocols above and many other newly proposed MAC protocols are designed for sensor networks because of the relatively low cost of a class of sensor nodes that run on TinyOS [12] and the easy-to-use programming interface provided by TinyOS [12]. We note that the use of limited capability sensor MAC protocols in MANETs results in severe performance penalties.

In this paper, we design and implement a hybrid CSMA-TDMA MAC protocol for MANETs to which we refer as Load-Adaptive MAC (LA-MAC) protocol. While the design of LA-MAC leverages some of the useful concepts of [9], [13], [14], and [11], LA-MAC is specifically designed for MANETs unlike most of its predecessors. To that end, LA-MAC is designed and implemented to run on MANETs formed by MIMO-equipped USRP [15] nodes. The protocol is intended to behave similar to CSMA under low contention and TDMA under high contention conditions by dynamically switching its mode of operation. It uses lost ACK messages along with the neighboring nodes information to determine the contention level. LA-MAC eliminates the hidden terminal problem within a local contention area without requiring the use of RTS/CTS handshakes. Furthermore, it also addresses the synchronization problem commonly faced by slot-based MAC protocols.

The key contributions of this paper are as follows. First, we propose a MANET MAC design that combines the advantages of CSMA and TDMA while overcoming their shortcomings. Second, we design and implement a MIMO-OFDM PHY along with our proposed MAC in MANET nodes formed by a USRP and a host PC. Third, we utilize a cross-layer PHY-MAC design methodology to improve the performance of the protocol. Specifically, our protocol allows the PHY layer to provide the link quality metric to the MAC layer in order to

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control the mode switching behavior of the protocol based on actual collisions as opposed to MAC frame corruptions due to wireless link effects such as fading. We reiterate that to the best of our knowledge, leveraging advance capabilities of such MANET nodes for a MAC protocol has not been previously explored. Fourth, we provide a theoretical study to analyze the throughput of the protocol. Finally, we compare throughput, loss, and delay characteristics of our protocol to those of CSMA and TDMA alternatives both through analytical measurements and in a real MANET testbed formed by a collection of USRP nodes.

The remainder of this paper is organized as follows. Section II describes the internals of a MANET node used in this work. The implementation of MIMO-OFDM PHY is presented in Section III. Section IV describes the design, implementation, and throughput analysis of LA-MAC protocol. In Section V, we describe our experimental studies and analyze our results. Finally, we conclude the paper and discuss future work in Section VI.

II. MANET NODE DESCRIPTION

A review of the literature reveals the fact that due to the lack of appropriate experimental platforms, the performance of MAC protocols designed for MANETs has been mainly evaluated by means of simulations. While few commercial radio platforms such as WARP [16], CalRadio [17], and KUAR [18] have been made available, these platforms are typically expensive, not appropriate for mobility experiments due to a large Size Weight and Power (SWaP) characteristics, and not MIMO capable. Recently, there have been a number of MAC protocol development attempts due to the emergence of hardware and software platforms such as USRP, GNU Radio [19], and Click Router module [20]. Hydra [21] is a MANET test node that is comprised of a General Purpose Processing (GPP) host PC and a USRP system. A Hydra node uses Click Router module for its MAC implementation and consequently is incapable of maintaining precise scheduling synchrony. In [22], GNU Radio and Click Router module are used to create a primitive framework of TDMA protocol development. In [14], a new concept referred to as splitfunctionality is proposed in order to enable MAC protocol development for SDRs. Later on implemented on USRP-GNU Radio and referred to as inband signaling, the proposed approach places some time-critical functions such as precise scheduling, packet recognition, and radio control into FPGA in order to reduce host processing delay. An interface between the host and FPGA is also provided such that the host can coordinate with the FPGA. In our prior work of [23], we describe how to form a MANET testbed utilizing a collection of SDR nodes. Each MANET node consists of a GPP host PC running on Linux Operating System (OS) connected to a USRP motherboard and a pair of programmable RF daughter boards.

As illustrated by Fig. 1, such MANET nodes mainly operate relying on the following four components:

- **USRP** serves as the baseband processing and RF frontend of the MANET radio.
- GNU Radio [19] provides PHY and MAC layer functionality.



Fig. 1. The internal architecture of a MANET node including USRP and Linux network stack.



Fig. 2. The block diagram of the MIMO-OFDM transmitter and receiver.

- **TAP/TUN Interface** bridges TCP/IP and PHY/MAC together.
- Linux TCP/IP Stack supports NET-WORK/TRANSPORT layer functionality.

In our previous work, we use a MIMO PHY, GMSK modulation, and a CSMA MAC protocol available in the library of GNU Radio in each MANET node. In this work, we replace the PHY with a customized MIMO-OFDM PHY utilizing PSK modulation. Further, we replace the CSMA protocol by LA-MAC as the main subject of interest to our study. Finally, we rely on the use of message blocks (m-blocks) [24] in GNU Radio to implement LA-MAC. While the m-block framework was not used in our earlier work, its use facilitates the development of packet based LA-MAC protocol. It also allows for taking advantage of the inband signaling features discussed in Section IV-B such that the physical parameters of the radio can be controlled on the fly.

III. THE IMPLEMENTATION OF MIMO-OFDM PHY

In this section, we present our implementation of MIMO-OFDM PHY in USRP. Our implementation of MIMO-OFDM PHY leverages an open source library of IEEE 802.11n PHY described in [25]. This library supports many features specified in the 802.11n standard including space time encod-ing/decoding, channel estimation, and convolutional coding significantly facilitating our implementation of MIMO-OFDM PHY in USRP. Fig. 2 demonstrates the implementation of MIMO-OFDM PHY transmitter and receiver, respectively. We note that the input (output) of the transmitter (receiver) is provided by (to) the MAC layer. Further, the output (input) of the transmitter (receiver) is sent to (received from) the PHY layer.

As described by Fig. 2, Bit Scrambler randomizes the bit stream to prevent long sequences of zeros or ones. The channel

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encoder uses binary convolutional coding which has a base rate of 1/2 and can be punctured up to a maximum rate of 5/6. The coding rate can be dynamically changed based on the channel conditions. The spatial stream parser divides the coded input into multiple spatial streams. Then, block interleaving is applied to each spatial stream. Next, the modulator maps the sequence of bits onto constellation points associated with either Phased Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). The constellation size can be BPSK, QPSK, 16-QAM, and 64-QAM. When STBC is enabled, spatial streams are mapped to space-time streams by the spacetime block encoder. Then, pilot symbols are added to each spatial stream. Finally, the OFDM transmitter performs an IFFT and adds a cyclic prefix. At this time, the signal is ready to be sent out to the RF front-end.

At the receiving end, a frame is detected by the packet detector. The receiver then estimates and corrects the channel frequency offset. After synchronization, the receiver estimates the wireless channel making use of training symbols. Then frequency-domain equalization is applied to cancel the intercarrier interference. Afterward, the transmitter corrects the phase drift using pilot symbols inserted into every OFDM symbol. Finally, the bit information can be retrieved after applying space-time decoding, demodulation, and FEC decoding.

While we are not able to discuss the details due to the shortage of space, we make note of the most significant aspects of our implementation at the end of this section. First, the PHY implementation is capable of providing link quality metric measured in terms of SNR and passing it along with the decoded frame to the MAC layer in support of our crosslayer design approach. Next, we utilize multi-threading in order to take advantage of multi-core processors of MANET nodes. We note that the overhead of MIMO coding/decoding outweighs resulting performance advantages in the absence of multi-threading. We also extend the library to support the missing cases of $M \times N$ STBC antenna configuration in which M > N. Further, we correct and/or improve the performance of few of the signal processing blocks within the baseline library including channel estimation, phase offset, and FEC coding/decoding blocks.

IV. LA-MAC PROTOCOL

In this section, we present the design, implementation, and throughput analysis of LA-MAC protocol.

A. LA-MAC Design

LA-MAC may operate in two modes: CSMA and HYBRID. The protocol operates in CSMA mode when nodes have no knowledge of local network topology or synchronization within local contention area has not been established. The concept of local contention area will be described later in this section. This typically happens when nodes have newly joined the network and not yet been initialized. Otherwise, LA-MAC operates in the HYBRID mode blending CSMA and TDMA schemes of operation. When operating in HYBRID mode, LA-MAC can operate in a pure TDMA mode by disabling its slot competition algorithm described later in this section.

In CSMA mode, LA-MAC simply employs a random backoff mechanism similar to that of IEEE 802.11 MAC protocol. Specifically, within a contention window a node waits for a random backoff period before transmitting. Then, it senses the channel and if the channel is clear sends its data. Otherwise, the node waits and repeats the above process until it can acquire the channel. After receiving the data, a receiver sends an acknowledge (ACK) to the sender indicating whether the data was received correctly. If no ACK is received, the sender retransmits the data automatically. A node is always required to perform this carrier sensing process before transmitting data regardless of its mode of operation. In essence, CSMA mode is the baseline of the protocol operation which makes it possible for two nodes operating in different modes to communicate. CSMA mode is also used for exchanging the protocol's control information when network topology changes, for example, when nodes join or leave the network or move from one local contention area to another.

1) Initialization Phase: Noting that neighbor information collection and TDMA slot assignment are two important steps that need to be taken during the setup phase of LA-MAC, this subsection focuses on the initialization steps including dynamic time slot assignment and clock synchronization upon the startup of the protocol.

LA-MAC handles dynamic join and leave of nodes with the aid of Dynamic Time Slot Assignment (DTSA) [26] protocol. Each initialized node broadcasts its slot and frame information periodically. As a node joins the network or starts up, it first listens and acquires knowledge about its neighbors. Once the new node collects sufficient slot and frame information and synchronizes with the rest of network nodes, it can send REQ messages in the first slot of the frame reserved for uninitialized nodes. Then, each node receiving the REQ message replies with its one-hop neighbor list associated with corresponding slot assignment information. Eventually, the new node constitutes its one-hop and two-hop neighborhood information to which we refer as local contention area. Importantly, there is no need to gather neighbor information beyond two hops as the collision domain of nodes is limited to their local contention area. LA-MAC uses the neighborhood information to assign slots to each node. Additionally, the neighborhood information is also used for delivering the protocol's control messages in the normal operation phase. The priority-based slot competition algorithm described later also relies on the neighborhood information.

To avoid collisions without using RTS/CTS handshakes, LA-MAC uses the slot assignment algorithm of DTSA to assign new slots to a newly joining node. The protocol guarantees no two nodes within a two-hop neighborhood are assigned to the same slot. Recall that a conventional TDMA scheme accrues a high overhead related to propagating the maximum slot number necessary for the determination of frame length upon any network topology change. These shortcomings are overcome by changing the frame length adaptively. More specifically, a node is allowed to pick its own frame length according to the number of nodes in its local contention area. The use of such variable frame length mechanism yields two benefits, namely, i) fully utilizing time slots, and ii) significantly reducing the overhead of control messages because This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination. 4 IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, ACCEPTED FOR PUBLICATION



Fig. 3. The priority slot competition scheme used by LA-MAC.

a local network topology change no longer causes a global change. Once a new node picks its slots, it broadcasts the new slot assignment to all of its neighbors such that they can update their neighborhood information accordingly. At this point, the new node finishes the initialization phase and enters the normal operation phase.

While LA-MAC does not require maintaining global clock synchronization, it requires a node to maintain clock synchronization with other nodes in its local contention area. In our implementation, a designated node referred to as the base station facilitates its neighbors synchronization by sending synchronization (SYN) messages periodically. Since this processing requires the use of FPGA, it will be discussed in subsection IV-B2.

2) Normal Operation Phase: In the normal operation phase of LA-MAC, to which we also refer as the HYBRID mode of operation, a node can be in two states: Low Contention (LC) and High Contention (HC). A node is in HC state only when it receives a notification message from its two-hop neighbors. Otherwise, the node is running in LC state. In LA-MAC, a node can stay in HC state for a pre-defined duration of T_{HC} . If a node does not receive new notification messages during that period, it will go back to LC state automatically. While in LC state, all nodes are allowed to transmit in any time slot, implying that all nodes may run in CSMA mode. Nonetheless and unlike conventional CSMA, each node is assigned a priority and needs to compete for a time slot according to its priority. The owner of the slot possesses the highest priority against other nodes. Specifically, the priority of a node is associated with its Contention Window (CW). Suppose slot n begins at time t_0 and the owner of the slot is node A. Then the CW for node A is defined as $[t_0, t_1]$ while the CW for other competitors is $[t_1, t_2]$, where $t_0 < t_1 < t_2$. Fig. 3 illustrates the priority slot competition scheme used by LA-MAC.

Such dual-state operation can significantly improve channel utilization. Given a time slot, only the owner and its onehop neighbors can compete for the slot access under high contention levels. Thus, the collisions caused by the hidden terminal problem can be significantly reduced. Similarly, each node is assigned a priority in HC state and the slot competition follows the same strategy as that of LC state. In LA-MAC, the sender controls the switching of its own mode of operation. Fig. 4 illustrates the mode switching behavior of LA-MAC.

If a node (B) is experiencing a high collision rate, the packet loss rate tends to increase accordingly. As LA-MAC

Fig. 4. The state transition of LA-MAC.

does not use RTS/CTS to avoid collisions, the contention level is proportional to the collision rate. Therefore, the contention level can be estimated by counting the number of lost ACKs. If a sender (A) misses N consecutive ACKs associated with the mode switching threshold, a notification message is sent to all of its two-hop neighbors through node (B) informing them not to act as hidden terminals such that collisions can be avoided. Accordingly, the nodes which receive the notification message switch to the HC state. In subsection V-B5, we investigate how to optimize the mode switching of LA-MAC relying on our proposed cross-layer method.

3) Collision Avoidance: In IEEE 802.11 MAC protocol, the RTS/CTS handshake can be used to deal with the problem of hidden terminals. While it is inappropriate to implement the RTS/CTS handshake on the GPP host PC of a MANET node due to the excessive latency, offloading such functionality to the FPGA on USRP motherboard is not an option either due to inclusion of complicated functions such as modulation and demodulation. Hence, the implementation of RTS/CTS involves time-critical control and remains to be an open issue in GNU Radio. In LA-MAC, hidden terminal problems can be mostly mitigated by running in HYBRID mode. The probability of collisions caused by hidden terminals is small if the contention level is low. If the contention level is high, collisions within local contention areas are eliminated by notifying hidden terminals not to transmit.

B. LA-MAC Implementation

MANET nodes in our testbed are built on USRP and GNU Radio. GNU Radio runs on the GPP host PC and USRP is connected to the host via a USB connection. While USRP provides the RF front-end and baseband processing functionality, PHY and DATA LINK layers are implemented in GNU Radio. Generally, the FPGA chipset in USRP system converts the signal between the IF band and the baseband, resamples the signal, and then transfers the I/Q samples across the USB. All other signal processing functions such as modulation/demodulation and framing are completed on the host. Such architecture introduces significant latency as the speed of signal processing is limited by the computing capability of the host. Moreover, data transfer through USB is very slow. Given the fact that mainstream MAC protocols such as CSMA/CA and TDMA require a very strict timing for the transmission

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Fig. 5. The format of USB packets used for USRP inband signaling.

control, such approach is not suitable for the development of MAC protocols. While such timing requirements could be roughly satisfied by offloading time-critical functions to FPGA on USRP, control and status information exchanges between the host and USRP introduce further challenges. USRP interprets all data over the USB bus as samples and GNU Radio can only handle fixed length data with no metadata. In fact packet processing in GNU Radio was only made possible after message blocks [24] were introduced to support variable length data and meta-data. In light of the introduction of message blocks, a technique called inband signaling [27] emerged allowing for duplex communication between FPGA and GNU Radio components.

As illustrated by Fig. 5, the use of inband signaling allows for encapsulating samples sent over the USB interface in a new packet structure that includes additional information about the samples. This technique provides a control channel between the host PC and FPGA thereby enabling the exchange of information such as status. In our implementation, key functions such as carrier sensing, collision avoidance and synchronization are all built on top of inband signaling. We discuss such functions in the following subsections.

1) Carrier Sensing: In CSMA, a node senses the channel by computing the signal strength or noise level of the channel. If the signal strength exceeds some given threshold, the channel is busy. GNU Radio offers a basic Python-based implementation of CSMA working together with GMSK/DBPSK modulation. For a fair comparison of performance, we implement an identical CSMA protocol on the top of our MIMO-OFDM PHY to which we refer as GR-CSMA-MO. The host keeps computing the signal strength of the channel. Once it senses an idle channel, packets are sent out immediately. However, due to the transmission latency, it could be timeconsuming to get a signal sample through USB and compute the signal strength. Thus, when a host realizes that the channel is idle the channel has been actually idle for a while. The delay is the interval from the moment when signals are captured by the RF front-end to the moment when the processing of samples finishes on the host. In the meantime, other nodes may be allowed to transmit during this interval. If the host also sends packets at this time, collisions will occur. Inband signaling provides a potential solution to this problem. As illustrated by Fig. 5, there is an "RSSI" field in the metadata indicating the received signal strength as reported by the RF front-end. When a host receives samples, the channel state can be extracted from the RSSI information in metadata rather than computed from the samples. While this mechanism removes signal processing time, the transmission delay through the USB still cannot be ignored.

Coupled with inband signaling, LA-MAC's implementation approach calls for offloading the process of carrier sensing to FPGA. As soon as the channel becomes idle, the FPGA sends the packets out immediately. This translates to a 1-persistentCSMA system where a node transmits with a probability of 1 once it senses an idle channel. However, such approach may cause collisions when there are simultaneous transmissions. To avoid collisions, LA-MAC employs a random backoff algorithm. The host determines and signals the backoff time to FPGA relying on inband signaling.

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2) Clock Synchronization: The timestamp field in metadata is used for synchronization. The field is set by a 32-bit counter in FPGA that is incremented by the A/D sample clock. If the packet is sent to the host by the FPGA, the timestamp indicates the time by which the first sample of the packet was produced by the A/D converter. If the packet is sent from the host, the timestamp indicates the time at which the first sample of the packet should go out of the D/A converter. The sender schedules a SYN message to be transmitted at time T by specifying the timestamp field in the associated metadata. In the meantime, the sender also sets the timestamp in SYN message to time T. When the receiver receives the SYN message, it knows the time by which the packet is received relative to its local clock. Then, it can compare the difference between its local time and the sender's time. Our experiments results show that the inaccuracy of this synchronization is less than 10 microseconds which may be safely ignored for a link with a channel capacity of 250Kbps.

3) Transmission Control Algorithm: Combining carrier sensing and timestamp functionalities in FPGA, the transmission control algorithm of LA-MAC described below is implemented in FPGA.

Algorithm 1 LA-MAC Transmission Control Algorithm		
1:	Initialize CST (Carrier Sense Threshold)	
2: 1	Receive packet from host	
3 : i	if <i>packet.timestamp</i> is enabled then	
4:	if $packet.timestamp > fpga.timestamp$ then	
5:	return packet.tag {packet is dropped}	
6:	else	
7:	repeat	
8:	check fpga.timestamp	
9:	until $packet.timestamp \ge fpga.timestamp$	
10:	end if	
11: 0	end if	
12: i	if $packet.carrier_sense$ is false or $fpga.RSSI < CST$	
1	then	
13:	transmit (packet)	
14: 0	else	
15:	return packet.tag	
16:	end if	
15: 16:	return packet.tag end if	

C. Throughput Analysis of LA-MAC

In this section, the throughput analysis of LA-MAC is provided. Due to the low probability of operating in the HC mode in a one-hop neighborhood and since LA-MAC performs time synchronization in two-hop neighborhoods, 6

the throughput analysis focuses on the case of a two-hop neighborhood. Recall that LA-MAC switches its operating mode to the HC mode after it detects n consecutive collisions. After observing h collision free time slots, LA-MAC switches back to the LC mode. The LA-MAC repeats this pattern of mode switching periodically. Thus, the average throughput could be approximated with the average throughput of a period in which LA-MAC starts with the LC mode, switches to HC mode, and returns to LC mode. We base our analysis on the model proposed in [28] in which the performance of CSMA/CA is evaluated according to a Poisson distribution of traffic load in both single- and multi-hop MANETs.

In a MANET, an unsuccessful transmission results from collisions in a given time slot. For a one-hop topology, the probability of a successful transmission during a time slot with i backlogged nodes is given by:

$$P_{s}(i) = \frac{(M-i)g(1-g)^{M-i-1}(1-v_{i})^{i}}{1-(1-v_{i})^{i}(1-g)^{M-i}} + \frac{iv_{i}(1-v_{i})^{i-1}(1-g)^{M-i}}{1-(1-v_{i})^{i}(1-g)^{M-i}}$$
(1)

where v_i represents the probability with which each backlogged node senses the channel at the beginning of a slot, Mis the number of nodes in the neighborhood, and g represents the packet arrival rate during that slot. Then, the probability of at least one hidden node transmitting during the transmission period T_h of a time slot is:

$$P_{ht} = 1 - (1 - v)^{T_h \cdot M_{hb}} \cdot (1 - g)^{T_h (H_n - M_{hb})}$$
(2)

where H_n and M_{hb} denote the number of hidden terminals and the average number of the backlogged hidden terminals of a node, respectively. Thus, the probability of an unsuccessful transmission is expressed as:

$$P_u(i) = 1 - P_s(i) + P_{ht} \times P_s(i)$$
 (3)

The average number of time slots before n consecutive unsuccessful transmissions is then given by:

$$C_n = \frac{P_u(i)^{-n} - 1}{1 - P_u(i)} \tag{4}$$

Hence, the overall throughput during the LC period is:

$$T_{LC} = C_n \times T_{2hopCSMA} \tag{5}$$

where $T_{2hopCSMA}$, the average throughput of CSMA in a two-hop neighborhood, is:

$$T_{2hopCSMA} = (1 - P_{ht}) \cdot T_{1hopCSMA}$$

$$= \frac{(1 - P_{ht}) \cdot \sum_{i=0}^{M} \pi_i P_s(i) T_p}{\sum_{i=0}^{M} \pi_i \{\bar{I}_i + 1 + P_s(i)T + [1 - P_s(i)]C\}}$$
(6)

In the equation above, π_i denotes the stationary probability of $N^t = i$ where the random variable N^t represents the number of backlogged nodes, \bar{I}_i denotes the average number of idle periods for $N^t = i$, and T_p is the packet transmission time.

Next, the average throughput of LA-MAC in the HC mode is computed. Essentially, LA-MAC avoids hidden terminal problem by confining a Collision Domain (CD) inside a onehop neighborhood while operating in the HC mode. Specifically, every node will be assigned a time slot for transmission in the HC mode. However and in contrast to a pure TDMA scheme in which each node can only transmit in its time slot, LA-MAC allows nodes in the same CD to compete for time slots thereby increasing bandwidth utilization. The hidden terminal problem is avoided in the HC mode by preventing nodes from competing with their two-hop neighbors for time slots. We now apply our analysis to the topology of significance for LA-MAC, a two-hop neighborhood. It is known that each two-hop neighborhood consists of two CDs. Under the assumption that nodes are uniformly distributed, there is an average of M nodes in a CD and a total of 2M time slots can be utilized. While nodes within one CD can transmit in the first M time slots, nodes in the other CD can only transmit in the next M time slots. The latter is equivalent to considering nodes within each CD operate in CSMA mode but can only transmit half the times. As explained earlier, LA-MAC stays at the HC mode for a period of h time slots. Thus with d denoting the number of the CDs, the throughput in the HCperiod is:

$$T_{HC} = h \times \frac{T_{1hopCSMA}}{d} \tag{7}$$

Since the total number of time slots contained within the interval starting from the beginning of the LC mode and finishing at the end of the HC mode is $C_n + h$, the average channel throughput of LA-MAC within that period is measured as:

$$T_{LA-MAC} = \frac{T_{HC} + T_{LC}}{C_n + h} \tag{8}$$

V. PERFORMANCE EVALUATION

In this section, we present sample results of our theoretical and experimental studies to evaluate the performance of LA-MAC protocol against GR-CSMA-MO and TDMA as the available GNU Radio MAC alternatives. In addition, we investigate how our cross-layer design can impact the performance of LA-MAC. We note that our TDMA implementation utilizes DTSA to assign time slots. Therefore, the term DTSA is used to represent TDMA in this section for the purpose of accuracy and clarity.

A. Experimental Setup

Our experiments rely on a MANET testbed in which each test node consists of a host PC and a USRP motherboard. Each USRP motherboard hosts a pair of front-end RF daughter boards. Since each daughter board is attached to a single antenna, each MANET node is equipped with a pair of antennas. When transmitting, each MANET node utilizes Space-Time Block Coding (STBC) method of [29]. When receiving, it utilizes Maximum Ratio Combining (MRC). The host PC includes a 2.4GHz Intel Core 2 Duo CPU, 1GB of memory, and runs Fedora Core 10 distribution of Linux OS. Our MAC protocol as well as MIMO-OFDM implementation run in the user space of Linux. The default antenna configuration is 1×1

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TABLE I HARDWARE CONFIGURATIONS AND PROTOCOL PARAMETERS ASSOCIATED WITH OUR EXPERIMENTAL MEASUREMENTS.

Host PC	Dell Latitude E6400
RF front-end	USRP & XCVR2450
GNU Radio	Revision trunk-20090708
Channel bandwidth	500Ksamples/channel/second
CW size for owners	2 ms
CW size for non-owners	3 ms
Time slot size	30 ms
Mode switch threshold (N_{th})	5
HC state duration (T_{HC})	5 s
Center frequency	2.48GHz
Modulation	QPSK
Coding rate	1/2
Number of data subcarriers	52
Number of pilot subcarriers	4
FFT/IFFT order	64
Guard interval	16



Fig. 6. The topology of our two-hop experiments.

unless otherwise stated. Other major hardware configurations and protocol parameters are summarized in Table I.

B. LA-MAC Performance Profiling

To fully investigate the performance of LA-MAC, two different network topology scenarios are considered in the numerical evaluations. While a one-hop scenario is used to evaluate the effect of CSMA Mode on maximum achievable data throughput and latency, those effects along with the effect of hidden terminals are investigated in a two-hop scenario.

In the one-hop scenario, 9 nodes are randomly distributed within a one-hop distance of one another. There are no hidden terminals and any node can directly communicate with other nodes. For simplicity, only one node is designated as the receiver and others are designated as senders. Since the data transmitted by a node can be received by all other nodes, this designation of a single or multiple receivers makes no limiting impact on our performance profiling results.

In the two-hop scenario, we evaluate the impact of the hidden terminal problem among other factors. The network topology used in the two-hop scenario is shown in Fig. 6. As illustrated by the figure, the senders are separated into two clusters for this scenario. Each cluster is a one-hop network topology consisting of 6 nodes. While any pair of nodes within a cluster can directly communicate, a pair of nodes belonging to different clusters cannot directly communicate. Two nodes are placed in the union of the two clusters. Those two nodes are able to communicate with all nodes directly. To satisfy



Fig. 7. The latency comparison of GR-CSMA-MO and LA-MAC operating in the CSMA mode for a random one-hop topology.

these requirements, transmission powers and receive gains are tuned carefully. In the experiments, we analyze performance using two metrics.

- *Maximum Achievable Data Throughput (MADT):* MADT is defined as the aggregation of all data traffic delivered to receivers per second when senders transmit best effort traffic. When measuring MADT, the payload portion of data traffic is accounted for but not the frame preamble, frame header, or CRC bytes.
- *Round Trip Time (RTT):* Essentially, RTT is a translation of the transmit latency caused by host signal processing and USB data transfer. Since it is difficult to directly measure transmit latency of a packet sent out by the RF front-end, RTT is used as an alternative of transmit latency.

Performance comparison results are provided against CSMA and DTSA. All of the reported results are associated with multiple runs of twenty minutes or longer.

1) The Effect of CSMA Mode on Transmit Latency: In this subsection, the average RTT is measured comparing the transmit latency of GR-CSMA-MO and the performance of LA-MAC when operating in CSMA mode as imposed by the topology of the experiment. We refer to the latter as LA-CSMA. The experiment is conducted on a point-to-point link with a capacity of 250Kbps. A "Ping-Pong"-like program runs on one side and sends 64Byte long packets. The other side transmits background traffic at a rate of 50Kbps.

Fig. 7 illustrates latency distributions of GR-CSMA-MO and LA-CSMA over 100 experiments. The results show that the average latency of LA-CSMA (60ms) is nearly 10% less than that of GR-CSMA-MO (67ms). The values of standard deviations are 23.5 and 18.1 in the case of GR-CSMA-MO and LA-CSMA, respectively. We justify our observations by alluding to the fact that (a) a GR-CSMA-MO sender employing an exponential backoff mechanism experiences a larger number of backoffs than an LA-CSMA sender employing a random backoff mechanism, (b) employing an exponential backoff mechanism results in a larger standard deviation value for GR-



Fig. 8. The throughput comparison of GR-CSMA-MO, DTSA, and LA-MAC operating in the CSMA mode for a random one-hop topology.

CSMA-MO than LA-CSMA, and (c) sensing the carrier purely on host in the case of GR-CSMA-MO introduces transmit latencies more than an order of magnitude larger than sensing it on FPGA in the case of LA-CSMA.

2) The Performance of a One-Hop Network: In the onehop scenario and for the case of LA-MAC, we force all nodes to operate in the CSMA mode by disabling the functionality of slot synchronization. We gradually increase the number of senders representing a scenario of increased contention. Each sender transmits with its maximum rate. We observe how the throughput changes as a function of the contention level.

Fig. 8 compares the MADT achieved by GR-CSMA-MO and LA-CSMA. As illustrated by the figure, the throughput of LA-CSMA is nearly independent of the number of senders because no collisions occur in the absence of hidden terminals and every time slot can be utilized to transmit. In contrast, GR-CSMA-MO illustrates a MADT drop when the number of senders exceeds one. When 8 senders transmit simultaneously, the MADT of GR-CSMA-MO is approximately 60% less than that of LA-CSMA. The observation shows that GR-CSMA-MO experiences a large number of corrupt packets due to collisions demonstrating the poor performance of carrier sensing. The performance decrease is attributed to the lagged knowledge of channel conditions at the host, i.e., the channel state information available at the host may not accurately reflect the current channel state due to the USB transmission latency and signal processing delay involved in carrier sensing. Additionally, the achieved performance is affected by transmission delay caused by transferring samples to the radio over the USB interface. The larger the combined delay, the greater the possibility of collisions, and the worse the achievable throughput. However, the carrier sensing functionality is implemented in the FPGA for LA-CSMA. Hence, LA-CSMA can significantly improve the performance of carrier sensing by eliminating USB transmission latency and signal processing delay. Due to the overhead of time synchronization and guard intervals between adjacent slots, the MADT of DTSA is less than that of LA-CSMA even when all senders transmit. DTSA does not exhibit any performance advantage over LA-CSMA in the scenarios of one-hop network. In the



Fig. 9. A throughput comparison of GR-CSMA-MO, LA-MAC operating in the hybrid mode for two choices of mode switching thresholds, and DTSA in our two-hop topology of Fig. 6.

case of multiple antenna configuration, a 2×2 link has a BER performance advantage over a 1×1 link in the rich scattering environment of our lab. Therefore, MADT improves from 2% to 10% going from a 1×1 link to a 2×2 link depending on the MAC protocol. Nonetheless, packet collisions are still the dominant factor affecting the MADT of all protocols.

3) The Performance of a Two-Hop Network: In this experiment, MADT and the associated average Packet Error Rate (PER) are measured as the number of senders varies in our two-hop scenario experiment.

As shown in Fig. 9 and under the default 1×1 antenna configuration, LA-MAC represents a reasonable tradeoff between CSMA and DTSA. With one sender, LA-MAC operates in CSMA mode and yields a similar MADT as GR-CSMA-MO. When the number of senders is relatively small, LA-MAC significantly outperforms both DTSA and GR-CSMA-MO by fully utilizing idle slots. It stays at a relatively high level of performance without much oscillation. In contrast, MADT dramatically drops for GR-CSMA-MO due to collisions related to hidden terminals and DTSA suffers from a significant wastage of time slots. When the number of simultaneous senders exceeds to 8 ($N_{th} = 5, 2 \times 2$), DTSA outperforms LA-MAC due to the overhead associated with sending notification messages and inevitable packet loss associated with mode switching. Note that the performance gap between LA-MAC and DTSA can shrink or expand by adjusting the parameters T_{HC} and N_{th} . While reducing N_{th} and/or increasing T_{HC} allow LA-MAC to behave more like DTSA and thereby improve MADT in HC state, such adjustments degrade the performance of LA-MAC when operating under LC state. In the case of 2×2 links, the curves demonstrate patterns similar to those of the case of 1×1 links. However, the throughput of 2×2 links is between 5% to 25% higher than that of 1×1 links depending on the MAC protocol.

Fig. 10 shows the average PER corresponding to Fig. 9. Due to the coding and diversity advantage, the PER of 2×2 links is between 6% to 55% less than that of 1×1 links depending on the MAC protocol. DTSA exhibits the lowest average PER among the three MAC protocols due to the elimination of

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Fig. 10. The average PER comparison of GR-CSMA-MO, LA-MAC operating in the hybrid mode for two choices of mode switch thresholds, and DTSA for the two-hop topology of Fig. 6.



Fig. 11. The theoretical (T) and experimental (E) performance comparison of CSMA and LA-MAC in one-hop(1H) and two-hop (2H) networks.

hidden terminal problems all together. In the case of LA-MAC, a smaller value of N_{th} indicates that LA-MAC stays in the HC state for a longer time, thereby experiencing fewer collisions.

4) Throughput Comparison with Theoretical Results: Fig. 11 shows a throughput comparison of CSMA and LA-MAC in one-hop and two-hop networks as calculated by our analytical study and measured by our experimental study. The offered traffic load G denotes the total packet arrival rate of all senders divided by the theoretical channel capacity. Since LA-MAC and CSMA behave the same way in one-hop networks, their performance is identical. In theoretical results of twohop networks, LA-MAC exhibits a significant performance improvement over CSMA. The pattern of experimental results also matches those of analytical results validating our theoretical throughput analysis. The gap between the analytical and experimental curves for LA-MAC is related to the overhead of exchanging slot synchronization and notification control messages. Moreover, wireless channel effects also degrade the measured performance of the protocol.

5) The Impact of Cross-Layer Design on Performance: LA-MAC switches its mode of operation based on the number of



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Fig. 12. A throughput comparison of LA-MAC with its cross-layer feature (LA-MAC) and without its cross-layer feature (LA-MAC-NX) in effect for the two-hop topology of Fig. 6.

consecutive packet losses indicating the level of contention. As such, the protocol implicitly assumes that all packet losses are caused by collisions. However, it is known that wireless link effects such as fading can also cause packet corruption in wireless networks. Therefore, the performance of LA-MAC can be degraded by attempting at unnecessary mode switching if the dominant reason of packet loss is the poor quality of the wireless channel as opposed to actual collisions. As both anticipated and observed in our experiments, low channel qualities translate to low SNR values at the receiving end of the link. However, a MAC receiver cannot recognize a packet is corrupted as the result of actual frame collisions or poor channel quality. In order to differentiate between different types of loss, the MIMO-OFDM PHY reports the value of SNR to LA-MAC. Once received, LA-MAC compares the value of SNR with a threshold value in order to prevent unnecessary mode switching from LC to HC state and thereby improves performance.

Fig. 12 shows the performance improvement brought through this cross-layer design methodology. The results are in essence measured the same way as those of Section V-B3 except that the transmit power is reduced by 40% in order to introduce more packet errors caused by channel fading. When the number of senders is small representing a low contention level, the performance improvement is significant because most of the packet losses are caused by channel fading and LA-MAC can stay in LC state as long as possible. When the number of senders increases, collision becomes the dominant cause of packet loss and LA-MAC switches to HC state in any case. For the cases in which more than 4 senders are active, the throughput of both LA-MAC and LA-MAC-NX are comparable albeit small random variations of throughput exist.

VI. CONCLUSION

In this paper, we presented the design, implementation, and performance profiling of Load-Adaptive MAC (LA-MAC) protocol for MANETs. We noted that LA-MAC operates in CSMA mode for low contention levels associated with light

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traffic loads and switches to TDMA mode for high contention levels associated with heavy traffic loads. We also noted that LA-MAC offers an improved performance by utilizing a cross-layer PHY-MAC design to control the mode switching behavior of the protocol based on actual collisions as opposed to frame corruptions related to wireless link effects. We analyzed the throughput of LA-MAC and implemented the protocol in an experimental MANET testbed formed by a collection of USRP-based SDR nodes. Our analytical and experimental results revealed the fact that LA-MAC achieves a better throughput performance than TDMA over both oneand two-hop MIMO MANET topologies when the traffic load allows nodes to compete for unused time slots. Further, the experiments revealed that LA-MAC offers both latency and throughout advantages over CSMA. Currently, we are extending LA-MAC as an anycast MAC protocol such that it can assist routing decisions by passing link quality information to the NETWORK layer. Such cross-layer design can improve routing performance in both tie breaker and standard routing cost measurement scenarios.

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