PHY Aided MAC - A New Paradigm

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***Abstract*—Network protocols have traditionally been designed using a *layered* method in part because it is easier to implement some portions of network protocols in software and other portions must be implemented in hardware for performance reasons. These different implementation techniques enforce layer boundaries. In this paper, we show that with the advent of software defined radios, it becomes possible to blur those layer boundaries and produce higher performance network protocols as a result.**

In this paper we exploit a programmable physical layer and *simultaneous transmission* to have clients signal whether they have packets to send. By detecting the high energy at the simultaneous transmission, the AP gets the following information: a) which stations have packets to send and b) whether the traffic load is high, medium or low. Again, using the programmable physical layer, the AP schedules clients efficiently while wasting little of the spectrum on signaling overhead. The proposed protocol is a) fast, since no packet transmission is required for polling responses and all clients respond concurrently; b) reliable, as the poll response is contention free and c) scalable. We demonstrate the feasibility of implementing such a system using a FPGA based prototype software defined radio platform. We then show how the MAC protocol can scale using the QualNet network simulator and compare the performance to a contention based protocol.

I. Introduction

Wireless 802.11 [1] specific networks are contention based systems. A considerable amount of time is lost in contending for the medium, retransmissions, collision etc. Rodrig *et al* [2] have shown that only 40% of the transmission time is used for actual information transfer. Most of the reasons for this low utilization of the wireless medium involve the exchange of co-ordination packets between the AP and the client. Substantial time is also spent in decoding these co-ordination or control packets. Evidently, there is a requirement to improve the signaling mechanism in contention-based wireless networks while it is equally imperative to reduce contention in the network.

In a time-division multiplexing network, an AP has the primary control of the media and assigns time slots for client transmissions. This method ensures contention free data transmission and also requires proper signaling and information exchange between the two parties, usually using some form of broadcast messages and the subsequent acknowledgments from the clients. The unreliability of the wireless medium has always made reliable broadcasting a challenge. Much work has already been done on improving the Distributed Co-ordination Function in 802.11 MAC to improve fairness and throughput by modifying back-off algorithms or the contention window [3], [4], [5].

In this paper, we show that we can use the same multicarrier communication methods as used to implement high data-rate transmission mechanism to build very low-cost signaling methods that make time-division networking very practical. In this work we intend to go beyond the capabilities of a conventional software based MAC to a faster, reliable MAC design by including PHY layer functionality and use them for exchanging MAC layer information.

Multi-user communication requires some form of *orthogonality* between multiple users in the time or signal structure, as in Orthogonal Frequency Division Multiplexing (OFDM) that forms the basis of the 802.11a/g PHY [1]. OFDMA is the simultaneous access mechanism using OFDM that splits the available spectrum into a number of orthogonal non-interfering *subchannels*, as utilized in WiMax [6]. Each subchannel consists of a set of subcarriers with pilot tones required to capture the channel effect and perform equalization to aid signal recovery. In our protocol, we propose an additional use of OFDM/OFDMA. Different nodes use one of the available subcarriers to transmit few bits of important information, which can be easily recovered by using simple energy detection at the receiver. This collective mechanism of communication also eliminates the need for any pilot tones or modulation. However, the ability to distinguish simultaneous transmission is a challenge in communication protocols. Therefore such signals typically need to be fairly simple as we discuss later in section §II. Similar results can be achieved by CDMA systems as well. However, to detect CDMA codes transmitted by the clients, the receiver has to perform correlation for all the N clients/codes. The post processing of the signal is time consuming if an elimination process is used, or extremely resource consuming if N parallel correlators are used.

We provide a simple yet effective mechanism to detect simultaneous transmissions, which is utilized in the MAC layer. For example, think of asking a room full of people if they ate breakfast that day. Individuals could respond using voice, but humans have a hard time distinguishing all the streams of information. However, if people raise their hands instead, it's immediately clear who has and has not eaten breakfast. However, it's hard to get complex information, such as *what* someone had for breakfast, since the set of possible responses are so large.

Figure 1 illustrates how radios can simultaneously "raise their hands" using orthogonal frequencies. This waterfall plot shows energy at different frequencies (horizontal axis) over time (vertical axis). The wideband energy at the top of the

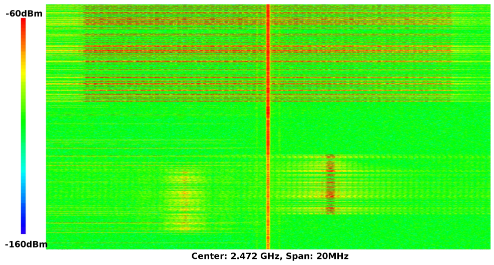


Fig. 1. Waterfall Plot Using Three Prototype Radio Platforms

figure is a broadcast packet asking nodes to respond if some condition is met; the two bands near the bottom of the plot are responses from two nodes. Later, we show that although the two nodes start transmitting at slightly different times and at different energy levels, it's easy to determine that two specific nodes have responded based on timing constraints.

Simultaneous transmissions can be an advantage in a number of network applications [7], [8] that call for multiple nodes to participate and also use simple information, like route requests, leader election, network management and other operations involving broadcast or multicast messages. Not only does simultaneous transmissions make the message exchange faster, it also allows such exchanges to be reliable by rapidly transmitting acknowledgments.

In this paper we emphasize that with a smart PHY layer which supports non-contiguous OFDM transmissions we build a more efficient, fast and variable time-division multiplexing MAC layer. We first demonstrate the feasibility of using physical layer signaling to exchange MAC layer information between nodes, addressing problems of near-far effects and time synchronization and coordination. We then describe the MAC layer protocol that uses the simultaneous signaling made possible by the programmable radio, and demonstrate its efficacy and scalability using QualNet simulations.

The rest of the paper is organized as follows. Section §II provides a detailed description of the physical layer signaling and the encoding methods needed to use it. Section §III describes the MAC protocol physical layer signaling. Section §IV describes the simulation infrastructure we used to evaluate the protocol under large scale conditions. We follow with a description of future work and conclusions.

II. Demonstrating Implementation Feasibility

In this section of the paper, we first establish that it is both feasible and practical to use both physical layer signaling and simultaneous communication.

Later, in §III, we focus on building an efficient MAC protocol by speeding *group communication* using *simultaneous transmission and reception*. Some group communication are caused by network protocols or applications, such as broadcast or multicast packets. However, the bulk of group communication in many wireless networks is used for coordinating media access *via* a contention based access protocol. An alternative mechanism is a time-division access protocol, similar to the Point Co-ordination Function (PCF) in the 802.11 MAC. Even these time-division protocols require exchange of control packets and signaling between multiple nodes.

We will show that such overhead can be reduced significantly if we allow all the clients to communicate with the AP simultaneously. For this implementation we have chosen the OFDM based physical layer for $802.11a/g$ as the underlying signaling.

A. Encoding The Signals

Assume the AP assigns each of the clients a unique subcarrier index which will be used by the client to signal information. Clearly, stations can use their individual OFDM subcarriers to transmit a single bit of information, such as "I have packets to send". However, it is also possible to send multiple bits of information without requiring any additional synchronization or hardware. For example, to implement a time-division or polling access protocol, an access point might need the clients to indicate: a) Who has packets to send? and b) Approximately how many packets do you have to send? Knowing the approximate queue length might let the AP implement various "fairness" methods by assigning different time slots to different clients based on their queue length.

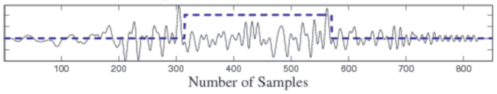
In such a scheme, the clients would all receive a single broadcast packet that effectively poses the question above. The clients might respond with one of four states (EMPTY, LOW, MEDIUM and HIGH queue). We encode these four answers by sending a BPSK modulated "1" or a "0" in their assigned subcarriers spread over four subsequent OFDM symbols.

B. Detecting The Signals

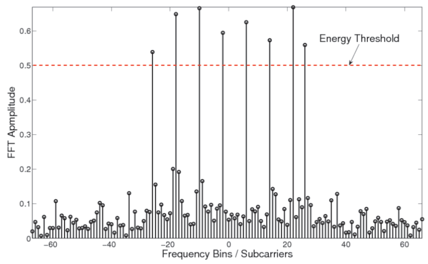
Figure 2(a) shows a composite waveform consisting of tones of different frequencies. The blue dotted line marks the optimum *Fast Fourier Transform* (FFT) window at the receiver. Figure 2(b) shows the magnitude of the Fourier transform of the composite waveform, revealing that 8 clients have actually transmitted tones, while other subcarriers remain idle. Thus, a suitable threshold is required to detect energy on the individual subcarriers.

Selecting the FFT window is key to successfully detect the energy of each tone from the clients. Due to near-far effects and the different processing power of the clients tones from different nodes that will reach the AP at different times. In a typical infrastructure network we assume that distance from the AP to the farthest node is $\approx 300m$, which implies a round trip delay of about $2\mu s$. There may also be delay from the transceiver turnaround time and hardware transfer times. Therefore we can define T as $T \geq 2 \times T_{propagation} + T_{r_x latency} + T_{hardware} + T_{t_x latency}$. Given that each OFDM symbol has a duration of $4\mu s$, we need to specify the interval T that the AP needs to wait before performing the FFT while ensuring that within that interval all nodes have transmitted their individual tones to signal about their queue status.

Figure. 3 shows the relative timing diagram and optimum FFT windows. Given a RTT of $2\mu s$ from the farthest node we start the FFT window after $3\mu s$. The precision of clock



(a) Composite Waveform



(b) FFT Magnitude

Fig. 2. Fourier Transform of the Composite Waveform

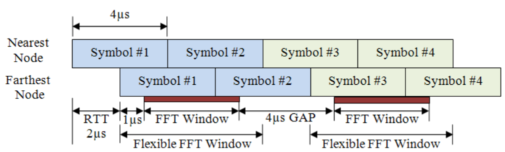


Fig. 3. Signal Timing Diagram

synchronization needed for this method is actually less than for normal 802.11g data payloads. Unlike single user OFDM transmission, strict receiver timing synchronization is not required since no demodulation is required despite receiving data from multiple clients – we are simply detecting "energy in the channel". Also, since these are unique single frequency tones, the OFDM subcarriers are transmitted without any PLCP header or any identifier which saves bandwidth and makes detection faster at the AP. This makes implementation fairly simple and straightforward, and the technique should be able to be implemented on commodity 802.11 hardware.

A normal message requires a $20\mu s$ preamble to be transmitted and then, at best assuming the 54Mb/s modulation rate, each 48×6 bits takes one OFDM symbol time ($4\mu s$) to transmit. Thus, a 64 byte message, which can't actually even contain the Ethernet addresses in a standard 802.11g packet would take at least $20+4\times3$ or 32μseconds. After a 2μsecond "SIFS" period, clients would normally respond using a similar message format. Thus, a single response to a standard 802.11g packet would take another $\approx 32\mu s$. By comparison, using physical layer signaling *53* clients can provide two bits of information (such as queue length) within four OFDM symbol periods, or a total of $16\mu s$, or only half the time for a *single* station to respond using standard messages.

C. Hardware Implementation

To demonstrate that the challenges to using simultaneous reception to implement our protocol are indeed tractable, we implemented a prototype using a software defined radio platform. The basic design involves an OFDM transceiver on a Virtex-IV FPGA along with a custom front-end radio [9]. The platform is capable of transmitting and receiving generic 802.11g frames as given in the 802.11 physical layer specification [1].

Implementing the protocol described in section §III requires transmission of *non-contiguous OFDM symbols*, where none but one of the subcarriers is used to transmit the information. This requires some changes in the transmitter design. The transmitter design has been detailed in [10] which employs a hybrid design allowing sufficient reconfigurability to perform such non-contiguous transmissions. The protocol requires the involvement of a reconfigurable transceiver as well as a MAC layer that controls the hardware to perform the required tasks.

Given that you can demonstrate almost anything using a Matlab simulation, we felt it was important to demonstrate the protocol using three prototype hardware nodes. One of the radios was used to transmit one broadcast packet using the standard 802.11a/g PHY specification. The receivers decoded the broadcast packet and prepare the ACK packet with information on their pre-assigned subcarrier and transmit. The receivers were placed at two widely-varying distances from the transmitter to highlight the impact of near-far differences in clients. The results from our hardware has been validated using a vector-signal analyzer as shown in figure 1.

III. Efficient MAC Protocol Using PHY Signaling

Much of the overhead of contention-based wireless networks arise from the network signaling for media access. One example is the 802.11 distributed coordination function (DCF) protocol, which has been reported to have up to 60% overhead due to the media access overheads and retransmissions due to errors [2].

In this section, we describe Physical layer Assisted MAC (PAMAC), a MAC protocol that is compatible with the 802.11 DCF phase, is modeled after the PCF (point coordination facility) protocol but uses physical layer signaling to further reduce signaling overhead. In §IV, we compare the performance of PAMAC to a conventional 802.11 DCF MAC; we were unable to compare the performance of PAMAC to the 802.11 PCF MAC due to limitations in our simulator.

Figure 4 shows a sample time sequence for PAMAC operation. The time line shows messages transmitted over time from left to right; darkened messages are transmitted by the AP and all other messages arise from stations. As described in §II, an access point using PAMAC must assign stations to specific "tones" or subcarriers used for physical signaling. Thus, the initial operation of the network would involve an advertisement for stations to join the schedule-based phase of the network operation; such a message may be occasionally repeated to allow nodes the choice to join or leave the scheduled phase. The "Join Request" message elicits "Join Response" messages from stations. Once a pre-specified join period has expired, the AP will start a schedule based operation period.

The AP will first transmit a "traffic map" frame that assigns stations to specific "frames" and "tones" within those frames.

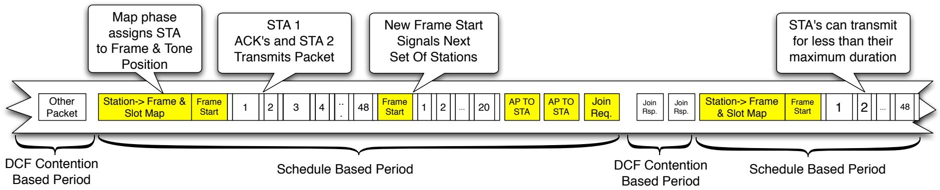


Fig. 4. Schematic Time Series Showing Protocol Operation - Darkened packets indicate packets sent by the access point and all non-filled packets are send by different stations.

In a small network, there would usually be a single frame; additional frames are used if the number of stations exceeds the number of subcarriers available for simultaneous signaling (*e.g.* 53 subcarriers for 802.11g). The "traffic map" frame is only sent when stations leave or enter the scheduled network operation.

Prior to sending "uplink" traffic from the stations to the AP, the AP sends a "frame start" message. Following the frame start, the stations reply with a tone sequence indicating if they have any messages to upload; all stations assigned a subcarrier or tone for that frame with a packet to transmit would respond simultaneously, as described in §II. The AP then transmits a single tone subcarrier indicating which station should transmit. Stations transmit for a fixed duration, possibly sending multiple messages during that period. If a station finishes before the end of the fixed duration, it can transmit a single tone on its subcarrier to indicate that it has finished transmitting; the AP will then indicate the subcarrier or tone ID of the next station that will be allowed to transmit. There are no hidden terminal problems since all transmitter wait to transmit until they are told to start, and the AP is in charge of designating which station should transmit.

Following the "uplink" phase, the AP transmits packets to stations using standard 802.11 packet encodings (*e.g.* also prepends a preamble, PLCP, *etc*), but transmits them in a continuous stream where stations ACK the packet and the AP then transmits the next downlink packet without releasing the media by starting transmission prior to the end of the SIFS interval.

IV. Result And Analysis Of Simulation Study

To evaluate the performance of the proposed protocol, we implemented an OFDMA based transceiver in QualNet [11], operating at $2.4GHz$, largely matching the capabilities and characteristics of our hardware platform. We compared the performance of the proposed protocol with the conventional IEEE 802.11a based MAC protocol provided by QualNet. We assume that the AP is in the middle of the scenario and all the clients are randomly distributed within a radius of $150m$. Thus, the AP is within the transmission zone of all clients, but all clients are not within the transmission zone of each other. Many similar random scenarios were used; a later example will illustrate the layout.

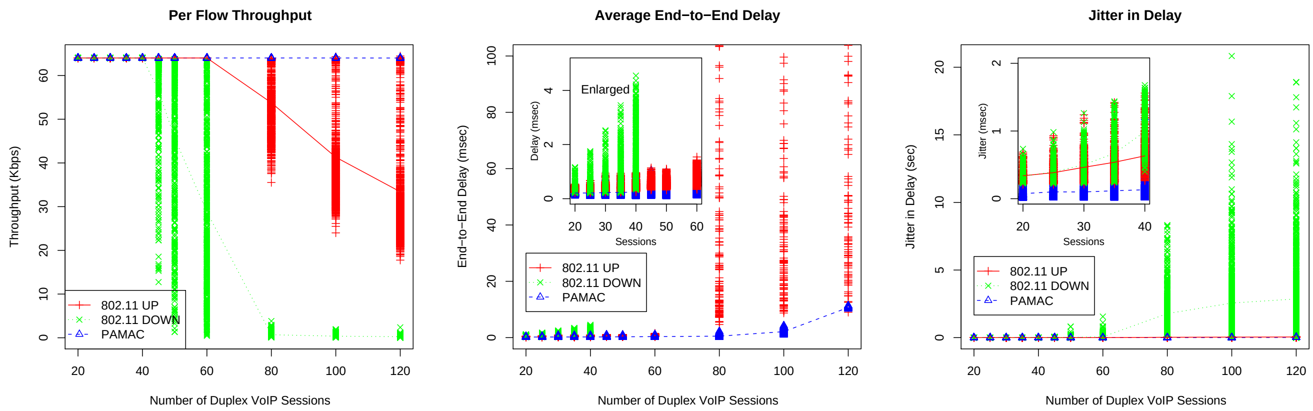
Our protocol is referred to as 'PAMAC', while the IEEE 802.11a based MAC protocol is refereed to as '802.11' throughout rest of the paper. Table I shows the parameters used for simulation. We evaluated our protocol for VoIP application, which requires low but constant bit rate for efficient quality of voice service. Since VoIP packets tend to be fairly small, this workload is representative of workloads that incur considerable signaling overhead; it is also an increasingly important protocol as the number of cellular phones using 802.11 to improve quality increases. All VoIP calls were full duplex sessions between a client and the AP. No client initiated multiple sessions.

TABLE I
General Simulation Parameters

Seeds	10
Packet Size (VoIP)	$120bytes$ (G7.11 codec)
Packet Arrival Interval	$15ms$ (G7.11 codec)
Physical Layer Data Rate	$36Mbps$
Simulation Time	$120secs$
Pathloss Model	Two-Ray
Application Layer	CBR
Transport Layer	UDP
Mobility	None

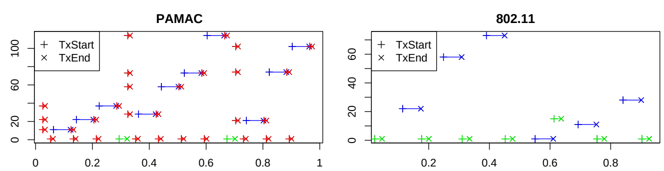
Figure 5 shows the performance of 'PAMAC' compared to standard '802.11', with increasing number of VoIP Sessions. PAMAC successfully caters efficient service to 120 clients, with almost no packet loss. The average end-to-end delay is significantly low, less than $20ms$, and the jitter in delay also remains low even at 120 duplex sessions. The end-to-end delays of the 802.11 protocol are much higher for larger numbers of stations due to queue overflow and we do not show that in the graph. Our protocol does fairly efficient communication even with 120 duplex sessions and call quality is maintained. The standard 802.11 MAC gets saturated beyond 40 concurrent sessions. The uplink and downlink flows in 802.11 shows distinctively different behavior. As network gets saturated, the AP builds a large queue of packets to send to the stations. Since the AP is using DCF, it does not get enough access to the medium depending on the cumulative traffic that is accumulated in its queue for all the clients. Hence, downlink sessions suffer more than the uplink ones. Other MAC protocols, such as Idle Sense [12] can resolve such unfairness, but they don't remove the overhead of contention.

Figure 6 shows how PMAC improves bandwidth utilization with compared to 802.11. The plot is a snapshot in time of $1msec$ duration. Node 1 has been designated as the AP and the other nodes are stations in the network. The *'red'*



(a) Throughput (b) Delay (c) Jitter

Fig. 5. Protocol Performance - G.711



(a) PAMAC (b) 802.11

Fig. 6. Bandwidth Utilization with Time

colored instances are tones, the *'blue'* timelines indicate packet transmission, and the *'green'* colored line denote the broadcast packets from the AP. It is evident from the plot that all the tone signals from the client happen simultaneously as defined in the protocol. On the contrary in 802.11 case, the shorter duration *green* signals are either ACKs or RTS/CTS. After contending for the medium data packets from the clients are transmitted, shown in *blue*. The irregular arrangement of the arrows across time shows the contention period and significantly reduced utilization of the wireless medium.

V. Conclusion

We've shown that by using, rather than fighting against, the properties of the wireless physical media, we can develop robust signaling primitives that are both practical and allow innovative algorithms. We used a signaling method (OFDM) that is easy to understand and visualize, but the general technique is amenable to other methods of orthogonal signaling, such as CDMA or combined methods such as coded OFDM.

The critical insight is that we can combine the results from multiple clients using simultaneous reception in an efficient manner. We can use this mechanism to both make specific network functions, such as broadcasts, reliable, but can also use the primitives to implement higher level group communication and signaling protocols. As long as the queries require simple "yes/no" answers, there are a number of robust mechanisms to combine the signals. The question remains of how such functionality could be exposed to client and host operating systems, particularly since similar techniques are difficult to implement on non-broadcast networks.

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