Towards efficient medium access for 60GHz networks

Mariya Zheleva, Ashish Sharma, Sumit Singh, Elizabeth Belding, Upamanyu Madhow
University of California, Santa Barbara

1. PROBLEM AND MOTIVATION

Millimeter-wave networks have emerged as an important research direction. This drive is a result of the advancement in the millimeter-wave circuit design, coupled with the growing need for short range high bandwidth wireless deployments. New wireless technologies, such as Long Term Evolution (LTE) are able to achieve bandwidths of a few hundred Mbps, but they are still far from providing gigabit links. Furthermore, they run on centralized systems, which are costly and not trivial to build. These limit their applicability in various wireless deployments. At the same time, networks operating millimeter-wave range are able to meet all the afore-mentioned requirements by utilizing cheap *distributed* solutions.

The wave propagation in 60 GHz is fundamentally different from that in the 2-5 GHz range. First, these high carrier frequencies are significantly influenced by the Oxygen absorption, which results in *high path loss*. That is why we limit the radio coverage to a radius of 100m. Second, the transmission in the millimeter-wave range is *highly directional*, which introduces two important advantages: (i) it alleviates the high path loss caused by the Oxygen absorption and (ii) besides time and frequency, it fully utilizes a third degree of freedom: space.

Because of the directionality of 60 GHz antennas, the nodes are able to sense only in one direction at a time. This property causes the effect of deafness between neighbors. As a result, the traditional media access control approaches based on carrier sensing are infeasible for 60 GHz communication. Successful transmission demands that the transmitter and receiver antennas be both beam-formed towards each other at the time of transmission. Thus, precise node coordination is necessary for successful communication.

We develop a system that utilizes MDMAC [1] - a *decentralized* MAC protocol for 60 GHz networks. It provides a method for implicit node coordination, that allows convergence to TDM-like schedules for wireless networks in the millimeter-wave spectrum. We implement MDMAC framework on a commodity 802.11 hardware to evaluate its performance in a real testbed as well as to have the software support developed and ready for deployment once there is an actual 60 GHz platform available.

2. BACKGROUND AND RELATED WORK

Previous work in the area covers interference analysis for 60 GHz networks [3]. The authors prove a level of link abstraction that enables scheduling of transmissions between neighbors in the case of deafness - a characteristic that MDMAC design relies on.

Another project in the millimeter-wave range suggests a *centralized* system for opportunistic multi-hop transmission when there is blockage of the direct link between the access point and a client within the WPAN [4]. While this system proves to be effective at low cost for indoors deployment, it can not be applied for outdoors *decentralized* scenarios.

There is work on directional communications in the 2-5 GHz range, which aims at enhancement of WiFi performance [5]. Such solutions, though, still use omni-directional transmission for control. For this reason they are infeasible for 60 GHz uni-directional communication.

3. APPROACH AND UNIQUENESS

To the best of our knowledge, this is the first project that aims to investigate a MAC protocol suitable for highly directional 60 GHz networks via actual testbed study. We implement MDMAC [1] on a testbed of three x86 PCs running Linux and CLICK modular router [6]. The machines are equipped with Atheros 802.11a/b/g wireless cards and the MadWiFi driver [7], which allows higher wireless interface reconfigurability, needed for our implementation.

In the presence of immediate neighbor deafness, each node keeps track of the packet transmission history to achieve implicit coordination with the others. This history-awareness is referred to as memory-driven implicit node coordination.

Precise node coordination in a fully decentralized system demands accurate time synchronization. A detailed investigation of a synchronization mechanism is out of the scope of this work, yet we note that there are proposed distributed synchronization techniques [8].

Time is divided into frames, where each frame consists of certain number of slots. For the purpose of implicit node coordination, each of these slots is assigned a transmission state, that defines the allowed sender/receiver interaction within the slot. There are four possible states - Transmit (T), Receive (R), Idle (I) and Blocked (B).

A running example, illustrating implicit node coordination is presented in Figure 1. Node A wants to transmit to node B and it picks a free slot from its built-in transmission table to attempt a transmission. On successful reception of this packet, B sends an acknowledgement back to A. The current slot is then marked as dedicated for transmission in both A and B. The process of packet/ACK exchange between A and B continues in this particular slot in the subsequent frames,

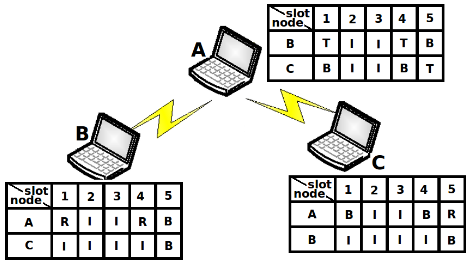

Figure 1: Utilizing MDMAC. A node running MDMAC maintains a data structure with states for each slot towards each neighbor. There are four possible states: ***T - Transmit, R - Receive, I - Idle, B - Blocked***.

until (i) there are no more packets left to be transmitted, (ii) B fails to send an ACK, or (iii) A fails to send a packet. After an initial set of iterations over the frame, all available slots are dedicated to the existing links and eventually the network converges to TDM with no explicit coordination.

There are two main drawbacks of the outlined protocol, which limit the fairness and effectiveness of the communication. First, the lack of free slots for new nodes, causes what we refer to as unfair locked transmission schedule. Second, this solution does not address the problem for dynamic resource reallocation in case of variable link utilization, which might lead to inefficient medium access.

To tackle these problems, we implement the following mechanisms. First, to prevent locked transmission schedules, nodes randomly reset their previously reserved and blocked slots. Second, we add a mechanism for explicit state reset, which assures that in case of slot allocation overload, the most demanding links will be taken off slots first. Third, for the needs of resource reallocation, each node keeps track of the utilization of its outgoing links.

4. RESULTS AND CONTRIBUTIONS

In a TDMA settings the accuracy of slot transition is extremely important. Miscalculation of the current slot might result in severe packet losses and compromise the time-divided transmission scheme. To meet the high slot transition requirements we implement a *scheduler*, which makes decision for transmission towards specific neighbor based on the current slot.

A node running MDMAC supports multiple outgoing queues - one per neighbor. We have implemented these queues at the software level, so that the scheduler is able to pull packets from the corresponding queue once it determines the neighbor to transmit to. The multiple queues concept is also utilized by the explicit state reset and slot reallocation mechanisms.

To be able to maintain transmission states, all nodes in the network support data structures with information about the state of each slot towards each neighbor (Fig.1). As our slot state updates are based on packet and acknowledgements transmission history we implemented a software-level *acknowledgement scheme*. We also designed a *data structure* which maintains the slot-state allocation, as well as a *mapper*, which keeps track of the packet transmission and updates the data structure accordingly.

As the time scheduling is performed at the software layer, one of the major challenges that we tackle is the control over transition of packets from the software queues to the hardware. Hardware queues could store up to few hundred packets and the actual transmission is done at best effort, which might not always be as per the upper layer schedule. To address this problem we estimated an upper bound of the number of packets that could be scheduled for transmission within a single slot. Our estimation is based on the expected time for transmission of one packet of certain size. In addition we have disabled random back off and retransmissions at hardware level to enhance the performance of our slotted transmission scheme.

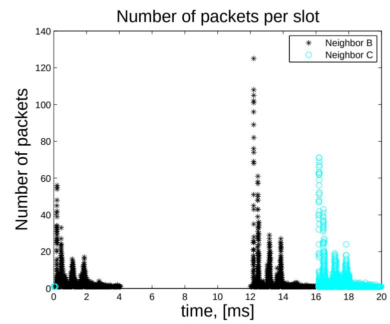

Figure 2: MDMAC transmission accuracy.

In our experiments, the time frame is 20 ms and consists of 5 equal slots. Figure 1 depicts our actual test scenario, in which node A transmits to node B in slots *one* and *four* and to node C in slot *five*. Figure 2 shows the number of packets transmitted for one minute within each dedicated slot. As we perform best effort scheduling, the packets are pulled from the corresponding queue as soon as the proper slot comes. This explains the peaks in the beginning of each slot. The results show that transmission is accurately done as per the schedule. As expected, the number of packets sent towards B (assigned two slots) is almost twice as the number sent to C (assigned one slot).

Our contributions in this work are as follows: (i) we make an actual deployment to evaluate the performance of medium access protocol designed for directional 60 GHz networks, (ii) we implement the software support for a millimeter-wave network access scheme, so that it is ready for deployment once a millimeter-wave platform is developed, (iii) we provide a software-level control scheme not to allow hardware properties to compromise our slotted transmission scheme.

5. REFERENCES

[1] Singh S., Mudumbai R., Madhow U., *"Distributed coordination with deaf neighbors: efficient medium access for 60GHz mesh networks"*, IEEE INFOCOM 2010, San Diego, CA, Mar. 2010.

[2] Sharma A., Belding E., *"FreeMAC: Framework for multichannel MAC development on 802.11 hardware"*, ACM SIGCOMM PRESTO'08 - Workshop on Programmable Routers for Extensible Services of Tomorrow, Seattle, Aug 2008.
[3] Mudumbai R., Singh S., Madhow U. *"Medium access control for 60GHz outdoor mesh networks with high directional links"*, IEEE INFOCOM 2009, Mini Conference, Rio de Janeiro, Brazil, Apr. 2009.
[4] Singh S., Ziliotto F., Madhow U. *"Blockage and directivity in 60GHz Wireless Personal Area Networks: From Cross Layer Model to Multi-hop MAC Design"*, IEEE JSAC, Special Issue on Realizing Gbps Wireless Personal Area Networks, 2009.
[5] Koraki T., Jakllari G., Tassiulas L. *"CDR-MAC: A Protocol for Full Exploitation of Directional Antennas in Ad Hoc Wireless Networks"*, IEEE Transactions on Mobile Computing, Volume 7, No. 2, February 2008.
[6] Morris R., Kohler E., Jannotti J., Kaashoek M. *"The Click Modular Router"*, ACM Transactions on Computer Systems (TOCS), Volume 18 , Issue 3, August 2000.
[7] *http://madwifi-project.org/*
[8] Sommer P., Wattenhofer R., *"Gradient Clock Synchronization in Wireless Sensor Networks"*, ACM/IEEE IPSN, 2009.