Evaluation of Medium Access Technologies for Next Generation Millimeter-Wave WLAN and WPAN

Carlos Cordeiro
Carlos.Cordeiro@intel.com
Intel Corporation, Hillsboro, OR 97124

Abstract — **The wide harmonized spectrum in the unlicensed millimeter-wave (60 GHz) band has been receiving increased attention, since it enables multi-Gbps data rates suitable for applications of next generation WLAN and WPAN such as wireless display, high-speed device synchronization, and the evolution of Wi-Fi. As such, the industry is in the process of defining new 60 GHz PHY and MAC technologies that can serve a wide variety of applications and usages, as to avoid the proliferation of non-coexistent devices operating in this unoccupied spectrum. Therefore, in this paper we discuss the challenges and trade-offs with three of the most "popular" medium access schemes, namely, CSMA/CA, TDMA, and Polling, in meeting the diverse requirements of the applications and usages envisioned for the 60 GHz band. We also analyze the throughput performance of each access technology and discuss a hybrid MAC that takes advantage of each access mechanism to meet the requirements of the envisioned usages and applications of 60 GHz WLAN and WPAN.**

Keywords: mmWave, 60GHz, multi-Gbps, MAC, WLAN, WPAN

I. INTRODUCTION

Worldwide harmonization in the unlicensed 60GHz band (also known as the millimeter-wave band) is generating increased interest for the development of physical (PHY) and medium access control (MAC) layer technologies that can serve a myriad of applications including wireless display, wireless docking stations, and next generation Wi-Fi [1][2]. The abundance of spectrum in the unlicensed 60 GHz band (up to 7 GHz) makes it feasible to achieve multi-Gbps link throughput, and hence offers the ability to enable a multitude of new usages and applications ranging from fast file synchronization between a handheld and a laptop to high-quality (un)compressed video distribution in the home or office.

While attractive, there are significant technical challenges for operation in the 60 GHz bands. For example, the signal propagation characteristics impose more challenges in terms of link budget than those at lower frequencies (e.g., 2.4 GHz and 5 GHz bands). Due to the inherent oxygen absorption, its high frequency and hence short wavelength, the signal attenuation in 60 GHz can be as much as 20 dB higher than in the 5 GHz band. Such high path loss has led to the use of high gain directional antennas at 60 GHz in order to compensate for the large path loss [3][4].

The use of directional antennas introduces several new challenges at the MAC layer. For example, aspects such as device discovery, spatial reuse and hidden node problems have been extensively studied [10][11][12][13]. However, the vast majority of the work done in this area has been primarily targeted at modifying the IEEE 802.11 MAC layer for operation with directional antennas at 2.4/5 GHz. To the best of the author's knowledge, there has been no work done to date on the evaluation and comparison of different MAC access technologies for operation in the 60 GHz band and how the different access technologies fit to the various applications and usages.

Therefore, in this paper we analyze three of the most "popular" MAC schemes and discuss their suitability in meeting the requirements of 60 GHz applications and also for dealing with the challenges for operation in the 60 GHz band. We highlight the pros and cons of each MAC scheme for 60GHz, present their performance in 60 GHz, and describe a hybrid MAC that can potentially fulfill the requirements of next generation multi-Gbps Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN) technologies.

The remainder of this paper is organized as follows. In Section II we discuss the usages and applications envisioned for 60GHz. In Section III, we analyze and compare three MAC schemes for operation in 60 GHz, namely, CSMA/CA, TDMA, and Polling. A hybrid MAC proposal is then described in Section IV. Finally, Section V concludes the paper.

II. 60 GHZ USAGE MODELS AND APPLICATIONS

The industry has been actively involved in developing technologies for the 60 GHz band within the context of WPAN applications (e.g., ECMA TC48 [3], IEEE 802.15.3c [4]), which typically operate within short range (e.g., around 10m) [8]. However, much less work has been done for WLAN applications. Thus, the IEEE 802.11 working group recently formed the 802.11ad task group (formerly "Very High Throughput" study group) to define an amendment to the 802.11 standard for operation in the 60GHz band. The standard created by 802.11ad will support data rates of at least 1 Gbps [19], hence enabling the next generation multi-Gbps WLANs (Wi-Fi). Table 1 shows how 60 GHz compares to other existing WPAN and WLAN wireless technologies.

The usages and applications proposed for 60 GHz do not change significantly from one standardization body to another. Hence, here we consider the usages provided by the Wi-Fi

Alliance (WFA) as input to IEEE 802.11 [9]. They cover a range of environments, including the home, office or enterprise, outdoor or hotspot, campus, and a factory floor. Both line-of-sight (LOS) short-range communication (e.g. on a desk or in a room) and non-line-of-sight (NLOS) long-range communication (e.g. entire home) are considered.

Table 1 – 60 GHz compared to other WPAN/WLAN technologies

	Wi-Fi (802.11n, 4x4) [5]	**UWB (WiMedia) [7]**	**60 GHz**
Frequency band (GHz)	2.4 and 5	3.1-4.7 and 6-7	57-66
Channel bandwidth	20 MHz and 40 MHz	> 500 MHz	2.16 GHz
Maximum PHY rate	600 Mbps	480 Mbps	Multi-Gbps (< 6 Gbps)

Usages such as wireless PC display, TV, or projector requiring uncompressed video will require data rates exceeding 1 Gbps. For example, the data rate for uncompressed 1080p with 24 bits/pixel and 60 frames per second is 3 Gbps. Video streams may be distributed simultaneously around the home to different displays requiring the wireless network to be capable of much higher total throughput than any one individual stream. Applications like sync-and-go or downloading movies or pictures from a camera require increasingly higher throughput as the quality increases. With a 1 Gbps wireless link, copying a 30 GB video file will take 4 minutes and a few hundred picture files each 20 Mbytes in size will take one minute. For data networking applications such as file transfer or data backup, wireless technology must keep up with the continued increases in wired capability and most new computers today already come with Gigabit Ethernet.

III. Evaluation of MAC Schemes for 60 GHz

As can be seen from Section II, the usages for 60 GHz are extremely varied in nature. Applications such as wireless display have very stringent requirements in terms of quality of service (QoS) guarantees and are very sensitive to delay and jitter. On the other hand, sync-and-go and Internet type of access are very sensitive to access latency (i.e., response time), but are less impacted by jitter and may not require bandwidth guarantees.

Therefore, here we analyze three of the most "popular" MAC schemes in use today for use in 60 GHz, highlight their pros and cons, and discuss their suitability to specific usage models as described in Section II. The three MAC schemes considered in this paper are:

- CSMA/CA: for example, used in Wi-Fi (IEEE 802.11) [5]
- TDMA: for example, used in cellular networks and WiMAX (IEEE 802.16) [16]
- Polling: for example, used in Bluetooth (IEEE 802.15.1) [17]

A. CSMA/CA

The main attractiveness of the CSMA/CA MAC protocol comes from the fact that it is robust and simple, and can operate reasonably well in overlapping network scenarios. CSMA/CA is also very suitable for carrying bursty type of traffic, since it provides a good balance of average access latency, average throughput and average link utilization [13]. On the downside, CSMA/CA is not particularly suitable for power management since it usually assumes stations to be awake. Also, although there has been significant work done in supporting parameterized QoS in CSMA/CA networks [6], complexity issues have impeded the adoption of this feature in products.

When applied to the specific case of 60 GHz, we need to look deeper into the design assumptions of CSMA/CA and how valid these assumptions are in 60 GHz. CSMA/CA [13] is founded on three key assumptions:

a) Receiver does not know who will transmit: therefore, to deal with this CSMA/CA requires stations to be capable of receiving omni-directionally
b) Carrier sense defer is effective only if all stations can detect the signal: thus, to accomplish this CSMA/CA requires stations to be capable of transmitting omni-directionally
c) Collisions cannot be completed avoided: hence, CSMA/CA uses random backoff for collision avoidance

As we can see, for both (a) and (b) it is assumed that omni-directional (or simply, omni) communication is needed. However, it turns out that omni communication in 60 GHz incurs a significant performance penalty. Figure 1 illustrates the data rate that can be achieved with omni communication in a NLOS 60 GHz channel, based on a link budget calculation using the parameters shown in Table 2. As we can see, at the nominal range of 10m the data rate using omni is over 600 times lower (around 6 Mbps) than that at close distances (around 0.4m). This has a major impact in CSMA/CA, particularly in the definition of its Slot Size. Figure 2 shows how the Slot Size is defined with respect to the RTS/CTS exchange in CSMA/CA.

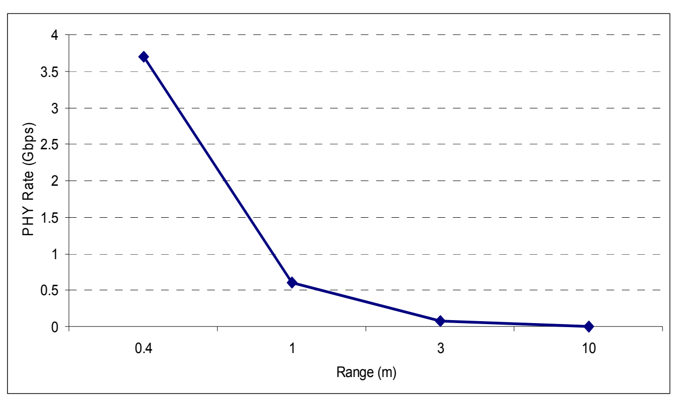

Figure 1 – Omni data rate as a function of distance

Table 2 – Link budget parameters for omni

Parameter	Value
TX power	10 dBm
TX/RX antenna gain	0 dBi
Obstacle loss	0 dB
RX noise figure	10 dB
Implementation loss	0 dB
Path loss	20 dB
Required SNR	18 dB

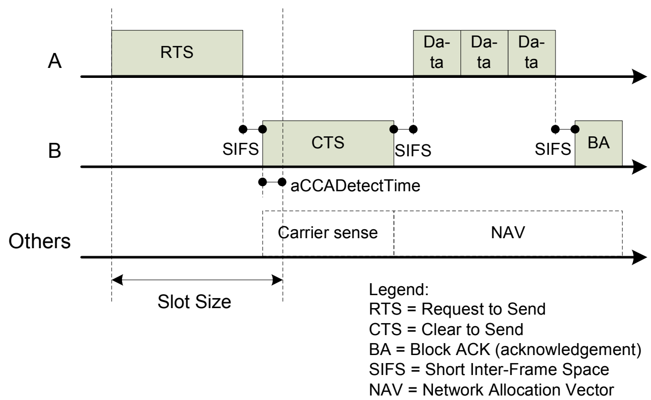

Figure 2 – CSMA/CA at 60 GHz

For CSMA/CA to be efficient the Slot Size needs to be smaller than the data frame transmission time. In 802.11 for the 2.4/5G Hz band [13], this is the case since the slot time is either 9 µsec (802.11a) or 20 µsec (802.11b) and the frame sizes are in the order of milliseconds. However, in 60 GHz the data frame transmission times can be a few microseconds due to the very high directional data rate (e.g., a TCP segment of 1500 bytes would take 4 µsec to be transmitted at 3 Gbps), whereas the Slot Size will be in the order of 32 µsec considering a 2 µsec preamble [4], a 2 µsec SIFS [4], a aCCADetectTime of 2 µsec, and a 20 bytes RTS as in 802.11 at a data rate of 6 Mbps. Using these values and an average number of backoff slots equal to two, Figure 3 analyzes the impact of the Slot Size on the CSMA/CA MAC efficiency at 60 GHz for different values of the transmission opportunity (TXOP) duration. Here, we define MAC efficiency as the time it takes to transmit a MAC frame payload divided by the total time needed to transmit the entire MAC frame including protocol overhead. Referring to the example of Figure 2, the MAC efficiency would be the time taken to transmit the payload in the 3 Data frames divided by the time taken by the Backoff + RTS + SIFS + CTS + SIFS + 3*Data + SIFS + BA.

As we can see from Figure 3, for a typical Slot Size of 32 µsec the efficiency of CSMA/CA is only around 25% for a TXOP of 50 µsec. And if we consider that at a 3 Gbps data rate it is possible to transmit as much as 15 Kbytes of payload over a 50 µsec TXOP, then it is possible to realize the dimension of the performance challenge a distributed CSMA/CA operation faces in the 60GHz band. For benchmarking purposes, in Figure 3 we also depict the performance of CSMA/CA for a Slot Size of 8 µsec which is similar to IEEE 802.11a Slot Size in the 5 GHz band. As we can see, at lower TXOP sizes the efficiency of CSMA/CA with Slot Size of 8 µsec is over 2 times higher than with a Slot Size of 32 µsec. For larger TXOP sizes, the efficiency gap naturally decreases given the larger payload sizes, but it is still sizeable.

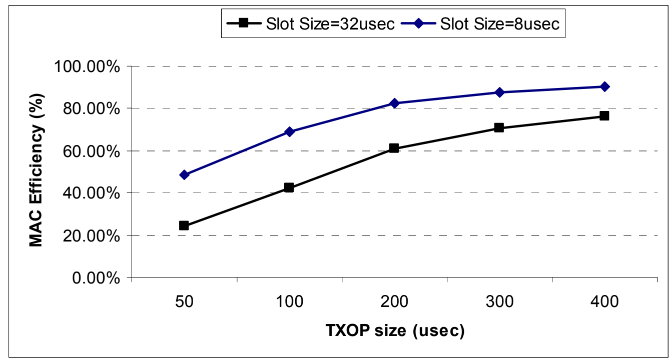

Figure 3 – CSMA/CA efficiency in 60 GHz

In addition to the performance issue, there are other important aspects for CSMA/CA operation with directional communication such as deafness and the fact that carrier sense may not be as effective as it is in the 2.4 and 5 GHz bands [13]. Therefore, there is a need to reconsider the CSMA/CA design for operation in the 60 GHz band, particularly given the fact that usages such as multi-Gbps WLAN is one of the key applications envisioned for 60 GHz.

B. TDMA

TDMA has enjoyed tremendous popularity in those technologies that are particularly sensitive to QoS, including WiMAX and cellular networks. Besides QoS, TDMA also has the benefit that it provides good support for power saving, since stations know the schedule of the network and can power down when not engaged in communication. Figure 4 depicts an example of a scheduled TDMA MAC, where the beacon includes the information about the ongoing communication between stations in the network.

When applied to 60 GHz usages, TDMA appears to be a suitable fit for applications such as wireless display (compressed or not) and large file transfers in sync-and-go. TDMA can provide the necessary bandwidth guarantee to these applications, while being power efficient. In addition, since TDMA is scheduled, stations know exactly to which other station they will communicate to and when, hence are able to steer the main lobe of their antenna towards the intended destination and obviate the need for omni as in CSMA/CA. Clearly TDMA needs some type of omni in order to support neighbor discovery, but during the actual communication omni is not needed. To illustrate this aspect, Figure 5 depicts the TDMA efficiency for different PHY rates and payload sizes, and which is calculated for a single Data-BA exchange. As expected, the TDMA efficiency increases with the payload size and is lower for higher PHY rates. Notably, for a payload size of 15 Kbytes the TDMA efficiency is over 80% which contrasts with a MAC efficiency of only 25% achieved with CSMA/CA (see III.A).

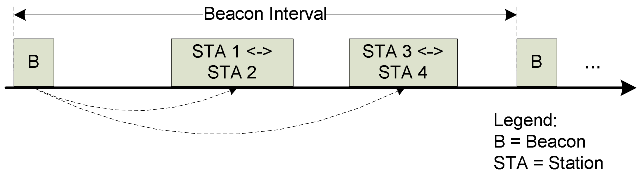

Figure 4 –TDMA at 60 GHz

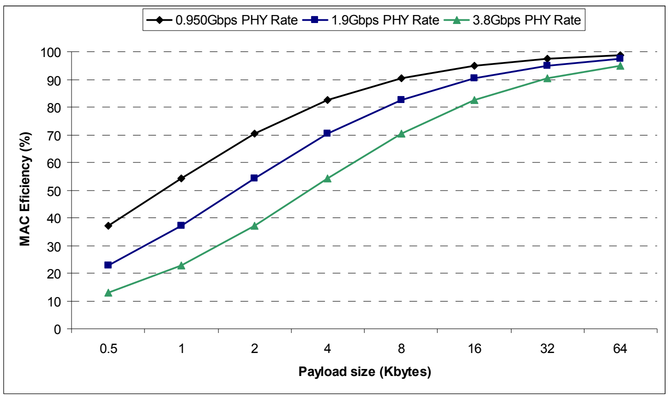

Figure 5 – TDMA efficiency in 60 GHz

TDMA is not without shortcomings though. All of the successful commercial deployments of TDMA have been primarily in licensed spectrum (e.g., WiMAX and cellular). For unlicensed bands such as in 60 GHz, a major concern in the use of TDMA is its robustness in the presence of overlapping networks. For home usages, robustness may not be an issue since 60 GHz signal propagation will most likely be confined to a room. However, in office environments with cubicles and conference rooms, it is critical to address the robustness issues. While some attempts have been made to increase the robustness of TDMA in unlicensed spectrum [14][15], these efforts have not taken 60 GHz specific requirements into account. Also, TDMA is not suitable for applications that require low latency channel access (e.g., Internet access, bursty traffic), due to the delay involved in making bandwidth reservation before a transmission can be made.

C. Polling

Polling is essentially a master-slave type of protocol wherein a central station (the master) polls the client stations (the slaves) to give them opportunity to transmit. In polling, slaves cannot transmit unless previously polled by the master. Because it is controlled by a central master node, polling provides a sufficiently simple MAC with good QoS support.

In 60 GHz, polling enjoys a few more important advantages than in lower frequencies. Since the access is controlled by the master, the slaves can by default always steer the main lobe of their antennas towards the master as depicted in Figure 6. With this, it is possible for the communication between the master and slaves to always use directional communications, and hence eliminate the need for omni. This not only can act as an interference mitigation scheme, but more importantly is extremely efficient since it allows the use of primarily the high data rates provided by directional transmissions. When compared to TDMA, note that polling may be able to exploit directional communication even further. While in polling all exchanges can be directional, TDMA may still require omni in order for stations to be able to make channel reservations.

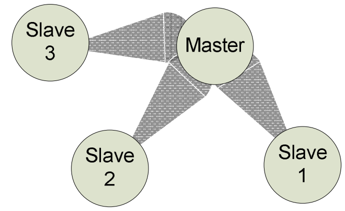

Figure 6 – In polling, slaves steer at the master

Figure 7 illustrates the polling efficiency in 60 GHz for the polling protocol depicted in Figure 8, and which is a modified version of the 802.11 HCCA polling protocol [6] adapted for directional communications. As we can see, the efficiency of polling is similar to that of TDMA at larger payload sizes, but drops below TDMA for smaller payloads. This is due to the fact that the access overhead for bandwidth acquisition is a separate process in TDMA and thus not computed into its efficiency, while in polling this process is built-in into the protocol. In addition, we can also see that polling is more efficient than CSMA/CA since it does not require omni but can perform all exchanges in high-rate directional mode.

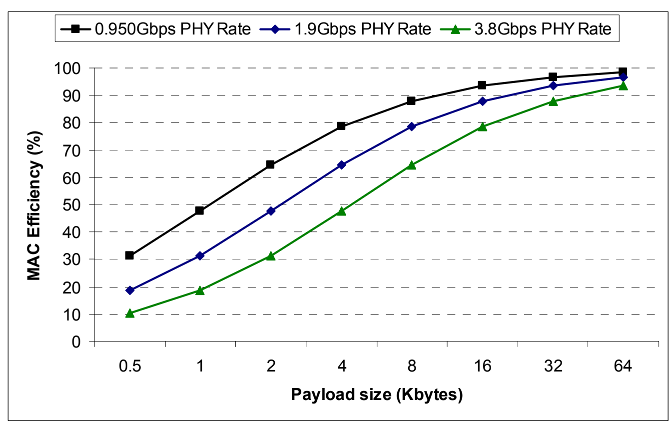

Figure 7 – Polling efficiency in 60 GHz

An important question to answer is what are the expected use of polling in 60 GHz. Polling can be used to support parameterized QoS similar as it is the case in IEEE 802.11e [6] which is based on CSMA/CA. If the MAC protocol is based on TDMA, however, polling may no longer be needed for providing parameterized QoS but has been shown to be an important scheme for bandwidth reuse when variable-bit-rate traffic is present in the network [18].

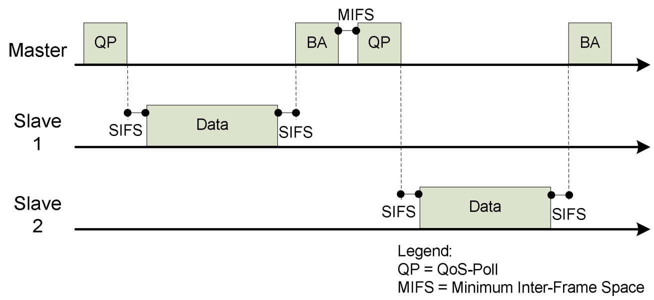

Figure 8 – Polling at 60 GHz

Like any other access mechanism, polling also has its drawbacks. Firstly, polling incurs higher power consumption at the master station which is responsible to carry out the polling function. Hence, mechanisms for power saving such as master handoff or low duty cycle polling are required. Secondly, polling is not suitable to take advantage of the statistical traffic multiplexing at the network stations. That is, with polling a master may poll stations that have no traffic to transmit, which leads to bandwidth wastage.

IV. A Hybrid MAC for the 60 GHz Band

As we can see, every access technology has its pros and cons in addressing specific 60 GHz usages and applications. No single access scheme seems to be able to meet all the requirements given the diversity of usages (wireless display, sync-and-go, wireless docking, etc) and platforms (television, laptop, handheld, etc).

Therefore, a hybrid MAC that is flexible enough to accommodate all the access schemes on an as-needed basis may offer the best trade-off in addressing the diverse requirements in 60 GHz. Along these lines, Figure 9 illustrates a hybrid MAC that includes support for CSMA/CA, TDMA, and Polling. In this hybrid MAC, the beacon is the element that is common across all network stations and serves to schedule periods of time during the beacon interval that can be used by TDMA, CSMA/CA or Polling. Therefore, depending upon the application, a suitable access scheme can be used.

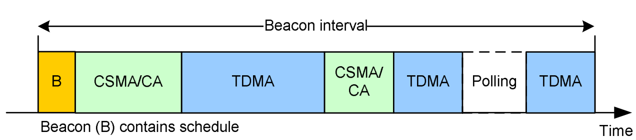

Figure 9 – A hybrid MAC for 60 GHz

While this approach may provide the required flexibility, it introduces complexity in implementation particularly for usages such as wireless computing which may require all three types of medium access schemes. Therefore, profiling may be required for 60 GHz so that different usages can be mapped to different access technologies, which allows for simplicity in implementation and interoperability.

V. Conclusions

The design of medium access technologies need to be revisited for the millimeter-wave (60 GHz) band. Challenges resulting from directionality, omni vs. directional data rates, and the diverse usages and applications, pose new and unique challenges that have not been previously addressed. In this paper, we have evaluated three of the most popular MAC schemes and concluded that neither one of them alone can meet the requirements arising from the diverse usages envisioned for 60 GHz. We then introduced a hybrid MAC that accommodates the considered access schemes in a single framework, hence providing a flexible yet solid foundation for the 60 GHz band. We believe this hybrid approach can serve as the next generation 60 GHz WLAN/WPAN MAC.

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