International Journal of Control and Automation
Vol. 8, No. 4 (2015), pp. 421-434
http://dx.doi.org/10.14257/ijca.2015.8.4.39

# Medium Access Control for 60 GHz Wireless Networks: A Comparative Review

Rabin Bhusal[1] and Sangman Moh[2]

[1]*I&M Team, Telstra Corporation, Perth, Australia*
[2]*Dept. of Computer Eng., Chosun Univ., Gwangju, Korea*
*rabin_bhusal@hotmail.com, smmoh@chosun.ac.kr*

***Abstract***

*The 60 GHz wireless networks enable multi-Gbps local communications. With opportunities, however, there are many challenges because the physical wave characteristics of the 60 GHz band are quite different from those of the currently used 2.4 GHz and 5 GHz ISM bands. Moreover, there are many hot issues associated with the MAC (Medium Access Control) layer as the directional MAC protocols proposed for 2.4 GHz and 5 GHz cannot be directly implemented on the 60 GHz frequency because of different characteristics of the millimeter waves. However, no review on MAC for 60 GHz wireless networks has been reported in the literature. In this paper, we comparatively review standards and protocols of MAC in 60 GHz wireless networks for multi-Gbps communications. Opportunities and challenges are also discussed.*

***Keywords:*** *60 GHz, millimeter wave, multi-Gbps, medium access control, directional antenna, ISM band.*

## 1. Introduction

Wireless local area networks (WLANs) based on IEEE 802.11 standards, also commercially known as Wi-Fi, have become an integral part of our daily living, and this technology is being integrated into many devices like smart phones, laptops, and other consumer electronics. The rapid increase of throughput from 2 Mbps in 802.11 to as much as 600 Mbps in 802.11n has provided many opportunities and led to a new goal to achieve speeds in the Gbps range. However, traditional license-free ISM bands of 2.4 GHz and 5GHz lack sufficient bandwidth to support such high data rates. As a result, the millimeter (mm) wave ISM (Industrial, Scientific and Medical) band in the range of 60 GHz has provided a new possibility to transfer data at multi-Gbps rate.

60 GHz frequency band allocation in some countries is summarized in Table 1 [1], which states that a large range of bandwidth is unexploited in many countries. In Table 1, EIRP (Effective Isotropic Radiated Power) is the output power that would have to be emitted by an isotropic antenna to produce the peak power density observed in the direction of maximum gain. EIRP includes antenna gain and excludes losses in hardware. Transmit power is the total transmitted power that does not include antenna gain and hardware loss.

The 60 GHz frequency band means a 5 mm of wavelength and, thus, this spectrum has been classified as millimeter wave. Note that the term millimeter wave usually represents frequencies between 30 and 300 GHz, and wavelength ranges from 10 mm to 1 mm. Due to the smaller wavelength the hardware manufacturers are quite confident to manufacture devices portable enough to integrate this technology in a large variety of mobile computing, consumer electronics, and peripheral devices. The antenna size for this frequency spectrum will be reduced by a large proportion as the size of the antenna is directly proportional to the wavelength. Moreover, using an antenna array can make this technology portable and handy as 16 antenna elements can be packed in 1 cm2 when

ISSN: 2005-4297 IJCA

adjacent antenna elements are separated by half the wavelength. This property is extremely beneficial when developing small-form-factor devices [2]. For many years, these millimeter wave applications and features have been a major research area, but the limitation in hardware integration has been a big obstruction in its evolution. Recently, semiconductor company Willocity [3] announced chipset development for 60 GHz networks, and a chipset that supports three bands (2.4 GHz, 5GHz and 60 GHz) will be popular in the future.

**Table 1. 60 GHz Frequency Band Allocation in Some Countries**

| Region | Bandwidth (GHz) | Transmit power (dBm) | EIRP (dBm) | Frequency range (GHz) |
|---|---|---|---|---|
| USA/Canada | 7.0 | 27 | 43 | 57 – 64 |
| Europe | 9.0 | 13 | 57 | 57 – 66 |
| Australia | 3.5 | 10 | 51.7 | 59.4 – 62.9 |
| Japan | 7.0 | 10 | 58 | 59 – 66 |

The 60 GHz technology has been studied for more than a decade. However, most researches have focused on the physical (PHY) layer, including wave characteristics. As circuit and antenna technologies evolve, MAC protocols for the 60 GHz technology have been studied more recently. In this paper, the standards and protocols of MAC in 60 GHz millimeter wave technology are reviewed and compared. The open design issues, opportunities and challenges are also extensively discussed. To the best of our knowledge, no review on MAC for 60 GHz millimeter wave wireless networks has been reported in the literature.

The rest of this paper is organized as follows: In the following section, 60 GHz wireless networks are overviewed. In Section 3, important design issues of 60 GHz MAC are introduced. In Section 4, various standardization efforts are addressed. MAC protocols for 60 GHz wireless LANs are reviewed and compared in Section 5. The opportunities and challenges are highlighted in Section 6. Finally, the paper is concluded in Section 7.

## 2. 60GHz Wireless Networks

MAC deals with sharing a common channel among multiple devices. The primary MAC technique used in the IEEE 802.11 standard is called distribution coordination function (DCF), which is a carrier sense multiple access with collision avoidance (CSMA/CA) scheme. DCF is a contention based random access scheme, where the retransmission of collided packets is managed by the so-called exponential back-off rule [4]. Initially, it was designed for omni-directional antennas and lower frequency bands of 2.4 GHz and 5 GHz. However, mm waves have higher frequency as compared to 2.4 GHz and 5 GHz and, thus, they bring many issues for designing PHY and MAC layers.

The 60 GHz band is prone to very high free space path loss that is almost 21 dB and 28 dB more than that of 5 GHz and 2.4 GHz, respectively [5]. Thus, the transmission range becomes more limited because of high loss and government-regulated output power level as listed in Table 1. Furthermore, oxygen and other gaseous absorption are very high for the frequency band. So, a 60 GHz network needs a directional antenna which compensates for the high loss by directional gain. The MAC layer depends on the PHY layer parameters and DCF was originally devised to be implemented for omni-directional antennas. Therefore, it is not beneficial to implement DCF for mm waves directly.

Furthermore, an antenna array with multiple antenna elements is realizable due to the small wavelength of 5 mm. Since peak beam forming gain increases as the number of antennas increases, which gives 12 dB of peak antenna gain when 16 element antenna arrays are used. With a directional antenna there comes another issue of beam forming and correct direction tracking. Research is also being done to design antennas-on-chips that tremendously decrease the size of these devices, but the complexity in designing such chips and devices increases, as they have to maintain a high gain requirement and efficient neighbor tracking with beam forming protocols.

It is also important to manufacture low-cost circuits which can be integrated with the current 802.11 a/b/g/n networks. Moreover, if the system needs to be compatible with current 2.4 and 5 GHz systems, handover between different frequencies, modulations, coding schemes, and data rates need to be done without affecting the user experience. This is difficult because a streamlined connection between two frequency bands with different characteristics should be maintained. Also, if the communication is limited to line-of-sight it will not make considerable influence in the market, so non-line-of-sight communication needs to be achieved by using a directional antenna and reflected or non-direct waves. By considering these problems, a perfect design can be achieved.

## 3. Design Issues in 60 GHz MAC

The serious issues such as high free space loss, gaseous absorption, lack of penetration and bending capability [1] make the use of directional antennas unavoidable for the 60 GHz frequency. Moreover, because of highly-directional communication, the 60 GHz frequency brings more complications in designing efficient MAC protocols. Many MAC protocols have been designed for communication using directional antennas for 2.4 and 5 GHz frequency spectra, but those protocols cannot be directly implemented for 60 GHz because of the different physical and electromagnetic wave characteristics of the 60 GHz waves. Or course, all the issues in utilizing directional MAC in lower frequency bands of 2.4 and 5 GHz are still open. The most important issue is to track all the neighbors, where majority protocols usually assume that the locations of devices are known in advance [6]. Some protocols consider an additional mechanism like Global Positioning System (GPS) for location tracking while others use angle of arrival (AoA) measurement. However, the use of GPS is not feasible in an indoor environment, while AoA is too complex for practical implementation.

### 3.1. Complicated Neighbor Discovery and Deafness

With directional antennas and directional communication, the most severe problem for the MAC layer is to scan and trace neighbors. When directional communication is adopted, a device is blind to all directions except its current transmission direction. In Figure 1, when Nodes A and B are in a beam formed state, they are deaf to all the surrounding neighbor nodes. So, in order to control the medium access nodes, they have to know the location and direction of the neighbors, which is the most challenging issue. This problem of not being able to hear the neighbors which are in range of the node but are in the opposite direction of current transmission is called the deafness problem. This deafness problem could be solved by using omnidirectional RTS/CTS and directional DATA and acknowledgement, but this sacrifices spatial reuse, especially for the 60 GHz band which is infeasible because its omnidirectional range is much less as compared to its directional range, or the link would not be symmetrical.

### 3.2. Hidden Node Problem and New Hidden Node Proble

The hidden node problem and the new hidden node problem arise because of nodes not being aware about the current transmission state of their neighbors. For example, in Figure 1, when Nodes A and B are in a state of communication, Node X completes its ongoing transmission with Node 4 and tries to beam form towards B and sends RTS, which causes a collision at B. The solution for this kind of problem needs to be addressed in the MAC design. Furthermore, the traditional hidden node and exposed node problems need to be addressed and resolved in the MAC design.

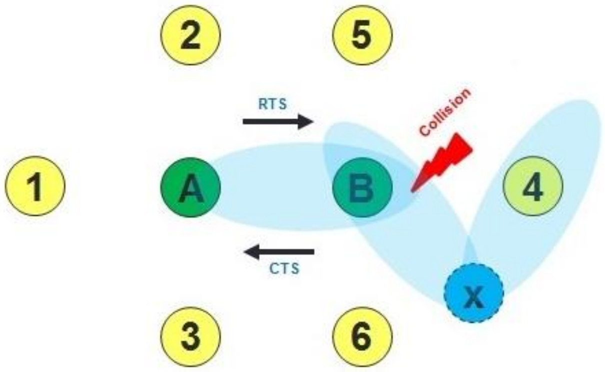


**Figure 1. Deafness, Hidden Node Problem and New Hidden Node Problem**

### 3.3. Antenna Training and LOS/NLOS Communication

Since implementation of a directional antenna is unavoidable in the 60 GHz frequency band and with the requirement to facilitate both line of sight (LOS) and non-line of sight (NLOS) communication, the issues of antenna training, antenna sector selection, and use of both direct beam and reflected beams for communication become relevant. This requires an efficient MAC protocol which can select the particular wave to make transmission reliable.

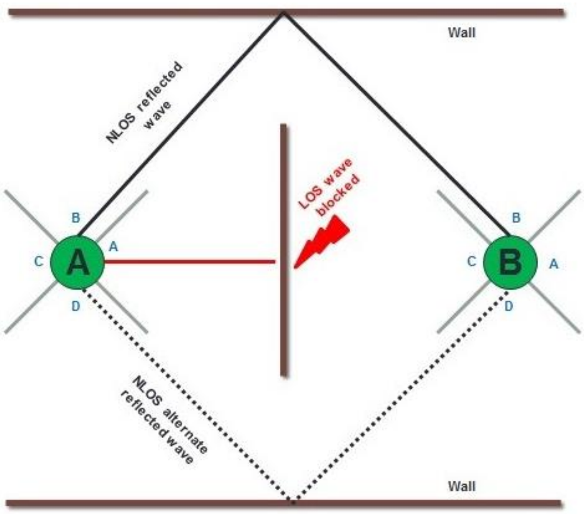


**Figure 2. LOS and NLOS Wave Selection by Directional Antennas**

In Figure 2, Nodes A and B are in ongoing communication with direct line-of-sight waves, and are using four sectored antennas. But in the meantime, some objects block the direct LOS component. In that situation, Nodes A and B must make a choice between multiple reflected paths, and the receiver must be able to continue communication without breaking the link. This is a major issue for MAC layer designers for 60 GHz communication, as it creates a poor user experience if there is break in the link or corruption of data, and because these problems might cause total implementation failure with this technology. Also, the use of a directional beam forming antenna makes the nodes very sensitive to movement and the selection of primary and secondary reflected paths for optimum transmission quality increases design complexity.

 

### 3.4. Transmission Range Extension

In order to discover the neighbor in all direction nodes that has to switch between an omnidirectional antenna and a directional antenna, because nodes with directional antennas alone cannot detect all the neighbors around them. So when the antenna switches between omnidirectional and directional modes, the range varies, because with an equal amount of transmission power, the range of a directional antenna is greater compared to an omnidirectional antenna. This makes it complicated for channel assignment by a MAC layer, because neighbors are discovered using an omnidirectional antenna, but not all the neighbors; which could be in the range of that particular node using a directional antenna.

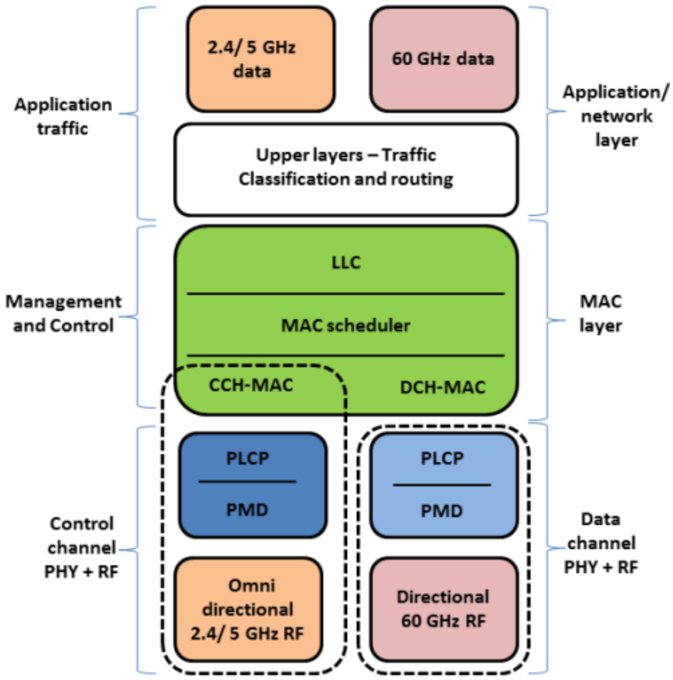


**Figure 3. 2.4 and 5 GHz Managed 60 GHz Network Protocol Stack**

### 3.5. Backward Compatibility to 802.11 a/b/g/n

The worldwide popularity, deployment, and acceptance of 802.11 a/b/g/n wireless technology have created a situation where its integration with any device is inevitable. So if this technology is to be integrated with the 60 GHz multi-Gbps technology, it can be used for neighbor discovery or for the transmission of control and management frames as in Fig. 3. Then the directional 60 GHz frames can be used to transmit synchronous, asynchronous, or isochronous high-speed data. Also, there must be smooth vertical handoff between both technologies in case there is some degradation in quality of service in either of the technologies, and the transmission of data has to be maintained. Moreover, the range of a 2.4 and 5 GHz Wi-Fi network is far more than the 60 GHz mm wave network, so the asymmetric range has to be balanced by a power control mechanism.

## 4. Standards

The enormous potential of the 60 GHz band to transmit up to 7 Gbps of data has provided many prospects. So, various standardization bodies and industry led consortiums compete to be the first to standardize this emerging technology, as listed in Table 2.

**Table 2. Comparision of Various Standards Being Developed for 60GHz Wireless LANs**

| Standard | Physical layer | Modulation and coding | Number of channels | MAC channel access | LOS / NLOS | Coverage | Data rate |
|---|---|---|---|---|---|---|---|
| IEEE 802.15.3c | Single carrier PHY | BPSK, QPSK,16 QAM | 4 | Centralized random and scheduled | Both | 10 m | 5 Gbps |
| | High-speed interface | OFDM | | | NLOS | | 7 Gbps |
| | A/V mode | OFDM | | | NLOS | | 7 Gbps |
| ECMA TC 48 | Type A | SCBT, OFDM | 4 | Distributed random and scheduled | Both | Max 10 m | Max 6.4 Gbps |
| | Type B | DBPSK, DQPSK, UEP | | | LOS | Max 3 m | Max 3.2 Gbps |
| Wireless HD | HMRP | QPSK, 16-QAM, 64-QAM | 4 | Centralized random and scheduled | NLOS | 10 m | 1-7 Gbps |
| | LRP | BPSK | 5 | | | | 2.5-40 Mbps |
| IEEE 802.11ad | Control PHY | DBPSK | 4 | Distributed contention channel access and scheduled access | Both | 10 m | 27 Mbps |
| | Single carrier PHY | DBPSK, QPSK, 16QAM | | | | | 4.6 Gbps |
| | OFDM PHY | SQPSK, QPSK, 16QAM, 64-QAM | | | | | 7 Gbps |
| WiGig | Low capacity device | Single carrier | 4 | Random and scheduled | Both | 10 m | 4.6 Gbps |
| | High capacity device | OFDM | | | | | 7 Gbps |

### 4.1. IEEE 802.15.3c

The IEEE 802.15.3 Task Group 3c (TG3c) was formed in March 2005. TG3c developed a mm wave-based alternative PHY layer for the existing 802.15.3 wireless personal area network (WPAN), 802.15.3-2003, which supports high data rates of at least 1 Gbps. Very high data rates in excess of 2 Gbps are provided for simultaneous time-dependent applications such as real time multiple HDTV video streaming and acting as a wireless data bus. This standard was ratified in September 2009 [7], and since November 2009, the task group has been inactive.

Three types of PHY modes are defined in this standard. The first one is single carrier mode, which focuses on low power and low complexity devices. The second is high-speed interface mode which is for low-latency bidirectional data transfer. And the third is for Audio/video (A/V) mode for the delivery of uncompressed high-definition video and audio. The MAC channel access method is centralized based on IEEE 802.15 personnel area network (PAN).

### 4.2. ECMA TC 48

The ECMA (European Computer Manufacturers Association) is a non-profit association of technology developers, vendors, and users [8]. In December 2008, ECMA TC-48 published the first edition of the standard ECMA-387, and in December 2010, the second edition was published, which specifies a PHY, distributed MAC sub-layer, and HDMI protocol adaption layer for 60 GHz wireless networks.

Similar to IEEE 802.15.3C, three types of devices (*i.e.*, Type A, Type B and Type C) are specified in ECMA 387 based on complexity and power. Type A devices are considered to be a high-end device and serve video and data over line-of-sight and non-line-of-sight with trainable antennas. These devices are the most superior as they are the most complex, consume a lot of power, and deliver the highest data rates. Type B devices are intermediate ones consuming moderate power and with less complexity compared to Type A, and are designed to deliver video/data in line-of-sight without using beam forming. Similarly, Type C devices are the least complex, have the lowest power consumption, and are used for data delivery over short range.

### 4.3. Wireless HD Constorium

Wireless HD is an industry-led Consortium formed in 2006 that consists of several leading technology and consumer electronics companies. The main target of this group is to enable wireless HDMI for streaming compressed and uncompressed A/V at up to 1080p resolution, and create a wireless video area network (WVAN). The wireless HD 1.0 specification was released in January 2008, and version 1.1D1 was released in May 2010 [9].

The wireless HD standard has defined two kinds of PHY modes, HMRP (High/Medium Rate PHY) and LRP (Low Rate PHY). HMRP inherits multi-Gbps throughput at a distance of 10m and is highly directional, for unicast only. LRP is a multi-Mbps link which is bidirectional and can both unicast and broadcast.

### 4.4. IEEE 802.11ad

The 802.11 standardization group is a market leader in wireless technology with the current 802.11 a/b/g/n standards and aims at achieving a 60 GHz multi-Gbps network. The organization formed the task group IEEE 802.11ad on January 2009 [10]. The amendment proposed to modify both the PHY and MAC layers of the 802.11 protocol to achieve very high throughput in the 60 GHz frequency band to coexist with the current 2.4 and 5 GHz networks, maintaining network architecture and backward compatibility with 802.11 management planes.

Three kinds of PHY layer modes are defined, which are Control PHY, Single Carrier PHY, and OFDM PHY. Control PHY is designed for low SNR operation prior to beam forming for training and controlling frame transmission. Single carrier PHY allows low-power low-complexity transceivers, and OFDM PHY is high performance and used for maximum data rate transmission. The channelization is similar to IEEE 802.15.3c for maintaining mutual compatibility.

### 4.5. Wireless Gigabit Alliance

The wireless gigabit alliance (WiGig) [11] is an industry-led organization promoting 60 GHz wireless communication. It was formed in May 2009 with large support from the personal computer, consumer electronics, semiconductor, and mobile handheld industries. The main target of WiGig is to unite different industries toward a trend of using a common standard of single radio technology so that interoperable and high-performance devices can be made to work together. Also, the WiGig Alliance, Wi-Fi Alliance, and VESA (Video Electronics Standards Association) have announced a cooperation agreement for multi-Gbps wireless networking and next-generation wireless display technology.

## 5. Medium Access Control

This section focuses on the MAC protocols designed for 60 GHz mm wave communication. The design principles of each protocol are reviewed and then different protocols are compared with each other.

The author in [12] proposes directional MAC using polarization diversity extension (DMAC-PDX), which utilizes the different behavior of linear and circular polarization of waves. The author uses those different behaviors of linear and circular polarized waves in conjunction with a Directional MAC protocol. This protocol has three basic steps, the first one being the detection of the presence or absence of a direct LOS path. The second step is the detection of transmission direction, and last transmission of data and acknowledgement is completed. To describe the first step in more detail, to determine the direct or reflected path, a test frame is simultaneously sent in all directions with linear and circular polarization using different frequencies or different time slots to avoid interference. Then the receiver compares the received power. If the difference in the received power of the first path for both polarization schemes are within a certain threshold ∆P, it is considered to be a direct path; otherwise, it is classified as a reflected path. Then if the transmission path is LOS, circular polarization is used to send back an acknowledgement (ACK/LOS) to the test frame; otherwise, linear polarization is used to send the acknowledgement (ACK/NLOS). The second step involves the detection of transmission direction by attaching a time stamp in the testing/synchronizing frame, which is then synchronized by the receiver. The difference in this time determines the delay in transmission. The RTS is sent in a circular manner in all directions with a time stamp. Then the sender stays in listen mode. In the receiver side, each time it receives an RTS from a different direction, it compares it with the local time and sends back a CTS frame to the direction from where the RTS was received and the local time was exactly matched. After the direction has been established, the data is transmitted using the particular network topology and antenna component. Both mathematical analysis and simulation shows better results compared to an omnidirectional MAC in [12], but the need to use dual polarized smart antennas, directional and omnidirectional antennas, and the long process of tracking, testing, and synchronization makes the protocol too complicated to implement.

The author proposes a CSMA/CA-based MAC protocol specially tailored for 60 GHz WPANs [13], [14]. It utilizes a Piconet controller (PNC) as a central co-coordinator for medium access. Before associating with a PNC, devices first perform beam forming training for both transmission and reception such that both the transmitter and receiver antennas can provide maximum gain. The devices always beam form towards a PNC in its idle mode, and while in receiving mode, the PNC always stays omnidirectional. In this configuration, devices can communicate with each other without bridging data to the PNC, but via coordination with the PNC. For example, if Device A wants to communicate with Device B, first Device A has to send a TRTS (Target Request to Send) to the PNC. TRTS has the address of Transmitter A, the PNC, and Receiver B. Then the PNC will send a TCTS (Target Clear to Send) in omnidirectional mode which contains the address of the PNC, Device A, and Device B. Here, since only one end of the device is in directional gain, the modulation and coding scheme must be chosen so that the range is higher. So, after TRTS/TCTS exchange Nodes A and B form beams towards each other, the transmission of high-rate packets are performed, and block acknowledgement is sent after receiving multiple packets. Furthermore, for the improvement of spatial reuse, the PNC first schedules a link to transmit data and schedule interference at each peer link. Based on the measurement, the PNC assigns non-interfering peer links into the same group, which can be scheduled to simultaneously transmit. By this way, spatial reuse is improved, but the antenna training, neighbor detection, beam forming, and interference measurement procedures are not addressed in detail.

In [15], the author proposes an IEEE 802.11 power saving mechanism (PSM) with an ad hoc traffic indication message (ATIM) window to solve the hidden terminal problem in 60 GHz directional communication. Here, time is divided into beacon intervals, and a small window called the ATIM window is placed at the start of each beacon interval. In this window, the nodes that have packets to transmit exchange control packets (RTS/CTS) before transmitting DATA. An RTS/CTS exchange is performed in the ATIM window using an omnidirectional antenna, and DATA and acknowledgements (ACK) are sent using a directional antenna.

In [16], the problem of neighbor discovery and the problem of asymmetry because of switching between omnidirectional and directional antennas are mitigated by making small changes in the 802.15.3 MAC. The author proposes a cross-layer scheme to achieve cooperation between the MAC and PHY layers, and the MAC layer takes initiative to control the modulation and coding schemes (MCS) and antenna modes at the PHY layer. An omnidirectional antenna can achieve the same range as the directional antenna without changing transmission power by low data rate MCS, since a different MCS has a different signal-to-noise ratio (SNR) threshold. In general, a high data rate MCS requires a higher threshold, and vice versa. So the author uses three modes of transmission, low data rate (LDR) using omnidirectional antenna (OLDR), LDR using directional antenna (DLDR) and high data rate (HDR) using directional antenna (DHDR). OLDR is used to transmit control and management packets.

DLDR is used to transmit neighbor discovery-related packets, and DHDR is used for data transmission. One-hop neighbor discovery is performed using the angle of arrival (AOA) scheme, and one hop neighbor tracking is done by exchanging self-advertising packets. The link co-existence test is performed for spatial reuse, and if multiple transmission links coexist in the same channel without interference, then they can be arranged in the same channel time allocation (CTA) block via the directional transmission scheduling (DTS) algorithm. Data is exchanged using TDMA, and the spatial reuse capability and link utilization are improved. The simulation results show better performance in terms of system throughput and end-to-end delay in [17]. However, node mobility and neighbor discovery are not addressed in the simulation.

The necessary modification of IEEE802.15.3B has been proposed to be used as mm wave high data rate WPAN [18]. The author proposes automatic device discovery (ADD) and frame aggregation with unequal error protection (UEP) to achieve multi-Gbps communication using a super frame of a Piconet. Initially, in the device discovery procedure, a 64 super frame interval is defined, while beacons for necessary antenna directions are included one by one in a super frame out of 64. Then, in the CAP period, device association requests and responses are exchanged, and the CTAP period is finally used for data transmission. Using frame aggregation with UEP, the MAC service data unit (MSDU) is fragmented into sub-frames with the same length and information of the most significant bit (MSB). These fragmented packets are forwarded to the PHY layer, which inserts Forward error correction after each sub-frame and transmits. Thus, a higher data rate with increased accuracy and quality is achieved by the procedure.

A distributed MAC protocol that employs memory to achieve approximate time division multiplexed schedules without explicit co-ordination or resource allocation is proposed [19]. A Hello message is sent by nodes for neighbor discovery in all directions circularly, and the node then waits for a response. Then, time-divided frame slots are used for data transmission and receiving. The novelty of this approach is the use of memory to store time slots to be used to communicate and the direction of beam forming for each node.

**Table 3. Comparison of MAC Protocols for 60 GHz Wireless LANs**

| MAC protocol | Mode | Location tracking | LOS/ NLOS | RTS | CTS | DA TA | A C K | Device comple xity | Antenna | Mobility in simulation |
|---|---|---|---|---|---|---|---|---|---|---|
| ATIM window in 802.11 PSM [15] | Contention based | No | Both | Omni | Omni | Dir | Di r | Mediu m | Omni, direction al antenna | Simulation not performed |
| DMAC-PDX [12] | Contention based | Polarization diversity scheme, Propagation delay | Both | Cir. | Dir | Dir | Di r | High | Omni, Dual polarized smart antenna, Direction al antenna | No |

 

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Directional CSMA/CA protocol [13] | Contention based | No | LOS | Dir | Omni | Dir | Dir | Medium | Phased array, Steerable antenna | No |
| Directional CSMA/CA protocol with spatial reuse [14] | Contention based | No | LOS | Dir | Omni | Dir | Dir | Medium | Phased array, Steerable antenna | No |
| Rate adaptation based super frame and CTA to achieve spatial TDMA [16],[17] | Contention free | Angle of arrival and one hop neighbor tracking | Both | The channel access in Piconet is based on super frame, which contains three parts: beacon, contention access period (CAP) and channel time allocation period (CTAP) | | | | High | Adaptive antenna array | No |
| Automatic device discovery and frame aggregation in 802.15.3b for 802.15.3c [18] | Contention free | Automatic device discovery beacon frames | Both | The channel access in Piconet is based on super frame, which contains three parts: beacon, contention access period (CAP) and channel time allocation period (CTAP) | | | | Medium | Omni, Directional antenna | No |
| Distributed MAC protocol [19] | Contention free | Hello message and wait for response | LOS | The channel access in Piconet is based on super frame, which contains three parts: beacon, contention access period (CAP) and channel time allocation period (CTAP) | | | | Medium | Electronic steerable antenna array | No |

A list of MAC protocols proposed for mm wave high data rate communication is shown in Table 3. The mode in the second column represents whether the MAC protocol is contention-based or contention-free. The location tracking column gives the technique used to track and detect neighbors. RTS and CTS frames that are transmitted either using an omnidirectional or directional mode in different protocols are addressed in the table. In the case of 802.15 PAN-based MAC, Beacon, CAP, and CTA are used in the super frame format instead of RTS/CTS, and the actual multi-Gbps data transfer is performed in CTAP, which uses the TDMA technology, resulting in contention-free access. Also, with the increase in complexity of neighbor discovery and antenna training procedure, device complexity also increases, which is reflected in Table 3. The antenna column lists the type of antenna used in protocols as the MAC protocol depends on the type of antenna used, and in the last column lists whether or not mobility was considered in the simulation procedure. Fig. 4 classifies MAC protocols as centralized and distributed. In the former method, a central coordinator assigns the medium among various nodes while, in the latter method, a random contention medium access mechanism is used.

 

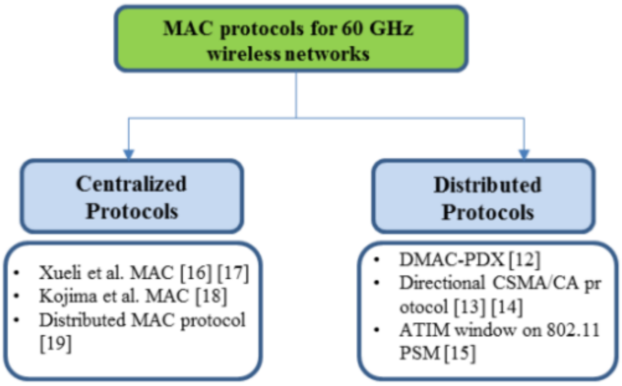


**Figure 4. Taxonomy of MAC Protocols for 60 GHz Wireless Networks**

## 6. Opportunities and Challenges

With a large proportion of bandwidth available in the ISM license-free spectrum of 60 GHz, there comes a lot of opportunities and challenges.

### 6.1. Opportunities

The wireless transmission of uncompressed HD video is possible because a large spectrum bandwidth is available at 60 GHz. Furthermore, the coverage of the 60 GHz spectrum is less due to higher path loss, lack of penetration capability and use of directional communication, the same disadvantages give a better opportunity of higher spatial reuse. Moreover, the size of the antenna drastically decreases as the carrier frequency increases, where the size of the antenna is directly proportional to the wavelength. And the development of the antenna array for directional communication is possible for this frequency band, limiting the antenna size to one square centimeter. Thus, the high free space path loss of the 60 GHz frequency can be compensated by using a directional antenna with a gain factor, and super high-speed wireless communication can be made possible. The existing market leaders operating within the 2.4 and 5 GHz band have paved a deterministic way for this mm wave to be integrated with them to provide a supreme experience to users, as every wireless communication device is coming with a built-in Wi-Fi interface, and both the increasing users and the limited bandwidth give a positive prospect for mm waves towards success. The market demand of gaming consoles like PlayStation and X-box further promises positive future as gaming activities require robustness and flexibility which can be provided by wireless integration.

Many applications of 60 GHz wireless networks can be explored with the availability of wide bandwidth, a high data rate of at least 1 Gbps, and a short transmission range of at most 10 meters. We summarize them below:

- Uncompressed video streaming and high-definition multimedia interface (HDMI) cable replacement to enable users to experience high-definition (HD) wireless video equivalent to that of wired video.
- Streaming of multiple uncompressed videos and distribution of HD television signals.
- Wireless gigabit Ethernet that makes it possible for multi-Gbps wireless bidirectional traffic for telecom backhaul networks.
- Office wireless desktops with only a power cable and ad hoc meeting rooms where large amounts of data are synchronized and transferred in seconds.
- Gaming, multimedia, and computing docking stations that allows multiple peripheral connections without the need for frequent connection and configuration setup.

 

- Multiband Wireless LAN supporting 2.4, 5, and 60 GHz tri-band frequencies for home, office, industrial, and medical network applications.

### 6.2. Challenges

Communication and information sharing is the key to success in enterprises and a way of living for today's society. There is no upper limit for the requirement of human nature and this nature brings superior technology and better innovative solutions. The 60 GHz bandwidth is the boon to bandwidth hungry multi-Gbps wireless communication. With such a beautiful technology there come challenges for implementation in a real scenario in the MAC and PHY layers. The higher the frequency band is, the greater the free space loss. Due to the large loss of signal that is almost 21 dB and 28 dB more than that of 5 GHz and 2.4 GHz, respectively, the coverage of the 60 GHz frequency is much smaller. Furthermore, the wavelength of this spectrum is very small, and this small wavelength causes waves incapable of penetrating through obstacles like walls, and also reduces the reflection capability of waves, which limits transmission range and creates a big challenge for NLOS communication. Also, the absorption of energy by gases like oxygen molecules, water vapor, and hydrometeors is very high for mm waves [20].

The backward compatibility issues also need to be taken care of so that the existing lower frequency and lower data rate Wi-Fi devices can connect with such devices. Moreover, multiple standardization organizations are creating different standards independently, which in turn create confusion to the consumers. In this case, the ECMA TC-48, 802.11ad, wireless HD and 802.15.3c standards use different procedures for communication because these groups are working separately to design a network that supports a multi-Gbps data rate. However, if the technology is different and devices are not compatible with each other, then there might be a negative influence in the implementation phase. Therefore, it can be inferred that a perfect design is the one that is compatible with every other device and can co-exist with previous Wi-Fi devices for mm wave networks. As people are already experiencing the mobility and robustness of current Wi-Fi technology, consumers do expect the same from 60 GHz communication. But different characteristics of the physical wave make it extremely complicated to give the same facility to consumers, though it can provide supreme data rates. Thus market penetration and consumer popularity are other big challenges for this technology to succeed.

## 7. Conclusions

In this paper, we have addressed the design issues, standards, MAC protocols, opportunities and challenges of 60 GHz wireless networks. The existing MAC protocols have been compared. The use of the 60 GHz spectrum in next-generation short range communication seems unavoidable as the lower frequencies lack of sufficient bandwidth. Despite the availability of around 7 GHz of license-free bandwidth at this frequency spectrum, problems like large free space loss, oxygen and gas absorption, and the requirement of directional antennas further complicate the design of efficient MAC protocols. However, a few MAC protocols have been proposed for 60 GHz networks, but the neighbor discovery, antenna training, and beam forming procedures make device complexity very high and infeasible to implement. So, there are many unexploited areas for researchers to design a more efficient MAC protocol to be implemented in the mm wave frequency and to make the multi-Gbps wireless network a reality, which will be in great demand for bandwidth-hungry applications in the near future.

## Acknowledgements

This A preliminary version of this work was presented at the 3rd International Conference on Smart Media and Applications, Dec. 2014 [21]. This work was supported in part by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2011744). Correspondence should be addressed to Dr. Sangman Moh (smmoh@chosun.ac.kr).

## References

[1] S. K. Yong, P. Xia, and A. V. Garcia, Introduction to 60 GHz, in: 60 GHz Technology for Gbps WLAN and WPAN: From Theory to Practice, 1st ed., John Wiley & Sons, **(2011)** pp. 1-16.
[2] E. Perahia, C. Cordeiro, M. Park, and L. L. Yang, IEEE 802.11ad: Defining the Next Generation Multi-Gbps Wi-Fi, Proc. of 7th IEEE Consumer Communications and Networking Conf., **(2010)** Jan., pp. 1-5.
[3] Y. Elborim and D. Meiri, The Future of Wireless Technology is Here: Introducing Truelly Wireless with wPCIe, White Paper, http://www.wilocity.com, **(2013)** Nov.
[4] IEEE, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Standard IEEE 802.11, **(2007)**.
[5] M. Park, C. Cordeiro, E. Perahia, and L. L. Yang, Millimeter-Wave Multi-Gigabit WLAN: Challenges and Feasibility, Proc. of IEEE 19th Int. Symp. on Personal, Indoor and Mobile Radio Communication, **(2008)** Sep., pp. 1-5.
[6] R. Bhusal, S. K. Timalsina, and S. Moh, Impact of Directional Antennas on Contention Based MAC Protocols in Ad Hoc Networks, Proc. of 8th Int. Conf. on Computing and Networking Technology, **(2012)** pp. 405-408.
[7] IEEE P802.15.3c - 2009 Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs): Amendment 2: Millimeter-wave based Alternative Physical Layer Extension, **(2009)** Sep.
[8] ECMA International Standard, ECMA-387 (2010), High Rate 60 GHz PHY, MAC and HDMIPAL, http://www.ecma-international.org/publications/standards/Ecma-387.htm, **(2014)**.
[9] Wireless HD specification version1.1D1, http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf, **(2014)**.
[10] IEEE 802.11 Task Group AD – Very High Throughput in 60 GHz, http://www.ieee802.org/11/Reports/tgad_update.htm, **(2014)**.
[11] Wireless Gigabit Alliance, WiGig White Paper – Defining the Future of Multi-Gigabit Wireless Communications, http://wirelessgigabitalliance.org/specifications/, **(2014)**.
[12] F. Yildirim and H. Liu, Directional MAC for 60 GHz using Polarization Diversity Extension (DMAC-PDX), Proc. of IEEE Globecom 2007, **(2007)** Nov., pp. 4697-4701.
[13] M. X. Gong, R. Stacey, D. Akhmetov, and S. Mao, A Directional CSMA/CA Protocol for mmWave Wireless PANs, Proc. of IEEE WCNC 2010, **(2010)** Apr., pp. 1-6.
[14] M. X. Gong, D. Akhmetov, R. Want, and S. Mao, "Directional CSMA/CA Protocol with Spatial Reuse for mmWave Wireless Networks," Proceedings of IEEE Globecom 2010, pp. 1-5, Miami, Florida, Jan. 2010.
[15] Z. Fan, Wireless Networking with Directional Antennas for 60 GHz System, Thoshiba Research Europe, **(2008)**.
[16] X. An and R. Hekmat, Directional MAC Protocol for Millimeter Wave based Wireless Personal Area Networks, Proc. of IEEE VTC-Spring 2008, **(2008)** pp. 1636-1640.
[17] X. An, S. Zhang, and R. Hekmat, Enhanced MAC Layer Protocol for Millimeter Wave based WPAN, Proc. of IEEE PIMRC 2008, **(2008)** Sep., pp. 1-5.
[18] F. Kojima, C.-W. Pyo, Z. Lan, H. Harada, S. Kato, and H. Nakase, Necessary Modifications on Conventional IEEE802.15.3B MAC to Achieve IEEE802.15.3C Millimeter Wave WPAN, Proc. of IEEE PIMRC 2007, **(2007)** Sep., pp. 1-5.
[19] S. Singh, R. Mudumbai, and U. Madhow, Distributed Coordination with Deaf Neighbors: Efficient Medium Access for 60 GHz Mesh Networks, Proc. of IEEE INFOCOM 2010, **(2010)** Mar., pp. 1-9.
[20] A. J. Richardson and P. A. Watson, Use of the 55–65 GHz Oxygen Absorption Band for Short-Range Broadband Radio Networks with Minimal Regulatory Control, Proc. of IEEE, **(1990)** Aug., Vol. 137, No. 4, pp. 233-241.
[21] R. Bhusal, C. Baek, and S. Moh, Standards and Protocols of Medium Access Control in 60 GHz Wireless Networks, Proc. of 3rd Int. Conf. on Smart Media and Applications, **(2014)** Dec., pp. D6.1-D6.5.

# Authors

**Rabin Bhusal** received his B.E. degree in electrical and electronics engineering from Kathmandu University, Nepal in 2006 and the M.S. degree in computer engineering from Chosun University, Korea in 2014. From 2006 to 2008, he worked as QA/QC inspector at Electrical and Instrumentation in Saudi Arabia and, from 2009 to 2011, he worked as a telecommunication engineer at ZTE corporation of China. Currently, he is an engineer at I&M Team, Telstra Corporation, Perth, Australia. His current research interests include 60 GHz millimeter wave multi-Gbps networks and wireless LANs with a focus on network architectures and protocols.

**Sangman Moh** received the Ph.D. degree in computer engineering from Korea Advanced Institute of Science and Technology (KAIST), Korea in 2002. Since late 2002, he has been a faculty member in the Dept. of Computer Engineering at Chosun University, Korea. From 2006 to 2007, he was on leave at Cleveland State University, USA. Until 2002, he had been with Electronics and Telecommunications Research Institute (ETRI), Korea, where he served as a project leader, since he received the M.S. degree in computer science from Yonsei University, Korea in 1991. His research interests include mobile computing and networking, ad hoc and sensor networks, cognitive radio networks, and parallel and distributed computing systems. He has published more than 150 papers in international and domestic journals and conference proceedings, and has held more than 40 overseas and domestic patents. He serves on the program committees of international conferences and workshops in his areas of interest. Dr. Moh is a member of the IEEE, the ACM, the IEICE, the KIISE, the IEEK, the KIPS, the KICS, the KMMS, the IEMEK, the KISM, and the KPEA.