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A Medium Access Control Protocol for Multiband Wireless Networks

Graduate School of Chosun University

Department of Computer Engineering

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멀티 밴드 무선 네트워크를 위한 매체 접근 제어
프로토콜

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Advisor: Prof. Sangman Moh, PhD

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버살 라빈의 석사학위논문을 인준함

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Acronyms

AoA	Angle of Arrival
ACK	Acknowledgement
CTS	Clear To Send
CSMA/CA	Carrier Sense Multiple access with Collision Avoidance
ECM-MAC	Energy-efficient Coordinated Multiband MAC
ECMA	European Computer Manufacturers Association
FCC	Federal Communications Commission
GPS	Global Positioning System
HD	High Definition
HDMI	High-Definition Multimedia Interface
IEEE	Institute of Electrical and Electronics Engineers
LOS	Line Of Sight
MAC	Medium Access Control
mm	Millimeter
NLOS	Non Line Of Sight
PCIE	Peripheral Component Interconnect Express
PNC	Piconet Controller
PHY	Physical
RTS	Request To Send
TDMA	Time Division Multiple Access
VESA	Video Electronics Standards Association
WiGig	Wireless Gigabit Alliance
WLANs	Wireless Local Area Networks
WPANs	Wireless Personal Area Networks
WVAN	Wireless Video Area Network

ABSTRACT

A Medium Access Control Protocol for Multiband Wireless Networks

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With the rapid development of bandwidth-hungry applications like wireless transmission of uncompressed high definition video, a multi-Gbps data rate is required at the physical layer. Due to bandwidth restraints on the 2.4/5 GHz ISM band, the 60 GHz millimeter wave spectrum with a large bandwidth of 7 GHz is increasingly used because it is capable of achieving very high data rates of up to 7 Gbps. However, the small coverage and unavoidable directional antenna requirement increase complexity and bring challenges for neighbor discovery and antenna training.

In this thesis, we first introduce the major challenges to design an efficient medium access control (MAC) protocol for the 60 GHz mm Wave frequency band. We highlight the deficiency of a single band MAC protocol and describe the requirement of a multi-band MAC protocol. Then, we propose an energy-efficient coordinated multiband MAC (ECM-MAC) protocol, which is capable of selecting a radio on the basis of required bandwidth and application scenarios. In the proposed MAC, the 2.4/5 GHz band with omnidirectional transmission capability is used for transmitting control and management frames, and the 60 GHz band associated with a directional antenna is used to transmit data at multi-Gbps speed.

Antenna training is done very efficiently, utilizing all 2.4/5/60 GHz radio bands, which not only significantly reduces the antenna training time but also saves remarkable amount of energy by using only one radio at a time.

According to the analysis results, ECM-MAC is 26% energy-efficient and takes 17% less time for antenna training compared to the conventional multiband MAC. Our simulation study shows that ECM-MAC outperforms the conventional multiband MAC in terms of average delay, energy consumption per bit and packet error rate.

한 글 요 약

멀티 밴드 무선 네트워크를 위한 매체 접근 제어 프로토콜

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비 압축 고화질 비디오의 무선 전송과 같은 고 대역폭 응용의 급속한 발전으로, Gbp급 데이터 전송률이 물리 계층에서 요구되고 있다. 2.4/5 GHz의 ISM 대역에서의 대역폭 제한으로, 7 GHz의 큰 대역폭을 갖는 60 GHz의 밀리미터파 스펙트럼의 사용이 증가하고 있다. 왜냐하면 최대 7 Gbps까지의 매우 높은 데이터 전송률을 달성할 수 있기 때문이다. 그러나, 작은 전송 범위와 불가피한 방향성 안테나의 사용은 복잡성을 증가시키고 이웃 노드 탐색과 안테나 트레이닝에서의 많은 문제를 야기한다.

본 논문에서는 먼저 60 GHz 밀리미터파 대역을 위한 MAC 프로토콜 설계하는데 있어서의 주요한 이슈들을 소개하고, 단일 대역 MAC 프로토콜의 문제점과 다중 대역 MAC 프로토콜의 필요성을 기술한다. 그리고 나서, 에너지 효율적인 협력 다중 대역 MAC 프로토콜(ECM-MAC)을 제안한다. ECM-MAC은 요구 대역폭과 응용 시나리오에 따라 주파수 대역을 선택할 수 있다. 전 방향으로 전송하는 2.4/5 GHz 대역은 제어 및 관리 프레임을 전송하는데 사용되며, 방향성 안테나를 사용하는 60 GHz 대역은 Gbps급 데이터 전송에 사용된다. 안테나 트레이닝은 모든 2.4/5/60 GHz 대역을 사용하여 매우 효율적으로 수행되며,

안테나의 트레이닝 시간을 크게 줄여줄 뿐만 아니라 한 번에 하나의 주파수 대역을 사용함으로써 에너지 소모를 현저히 감소시킨다.

성능 분석 결과에 따르면, ECM-MAC은 기존의 다중 대역 MAC에 비교하여 에너지 효율성을 26 % 향상시키고 안테나 트레이닝 시간을 17 % 줄인다. 또한 시뮬레이션 결과에 의하면, ECM-MAC은 평균 지연시간, 비트당 에너지 소비, 패킷 오류 발생률 측면에서 기존의 다중 대역 MAC을 능가하는 성능을 보인다.

I. 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 augmentation 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 Industrial, Scientific and Medical (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 band in the range of 60 GHz has provided a new possibility to transfer data at multi-Gbps rate.

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 adjacent antenna elements are separated by half the wavelength. This property is extremely beneficial when developing small-form-factor devices [1]. 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 [2] announced its final step towards chipset development for 60 GHz networks, and the major Wi-Fi card manufacturer Qualcomm Atheros has teamed up with Willocity to manufacture a chipset that supports three bands (2.4 GHz, 5GHz and 60 GHz).

A. Motivation

Frequency allocation and regulation have been governed by the US's Federal Communications Commission (FCC) and by responsible bodies in other countries. The frequency range and the allocated bandwidth are summarized in Table 1-1 [3], which state that a large range of bandwidth is unexploited in many countries.

Table 1-1. Frequency band allocation in various countries.

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

The availability of large bandwidth, which is license free, opens a door for many opportunities. Applications like the wireless transmission of uncompressed high definition (HD) video, bulk data transmission, and wireless data bus for HDMI (High-Definition Multimedia Interface) and PCIE (Peripheral Component Interconnect Express) cable replacements seems possible with the 60 GHz spectrum bandwidth. With hardware manufacturing being started there exist a requirement of medium access control (MAC) protocol which is robust enough to operate on this entirely new frequency spectrum as well as be able to be backward compatible to the current market leader 2.4/5 GHz Wi-Fi technology. With this statement in mind the main motivation of this thesis work is to coin a MAC protocol which can achieve a very high throughput in the range of 5 to 7 Gbps using 60 GHz mm wave frequency band which rectifies all the issues of the mm wave as well as is backward compatible to the Wi-Fi technology.

B. Problem Definition

This extremely high throughput of 60 GHz frequency band has made bandwidth-hungry applications technically feasible. This technology, however, brings many challenges. 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. Thus, the transmission range becomes more limited [4]. Furthermore, oxygen and other gaseous absorptions 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. Meanwhile, a directional antenna increases the transmission range and compensates for the loss of free space by the antenna gain factor. However, they introduce deafness and the hidden node problem. With directional antennas, the neighbor discovery and efficient antenna training procedure becomes very complicated, as directional antennas are not capable of either listening or transmitting signals in all directions [5].

C. Contribution

Multiband radio with 2.4/5/60 GHz can provide a promising solution for the problems stated. The 2.4/5 GHz band has low free space loss and is able to achieve larger transmission ranges with omni-directional antennas, while the 60GHz radio cannot acquire equivalent coverage even with directional antennas. In this thesis we propose a novel MAC protocol named ECM-MAC (Energy-efficient Coordinated Multiband MAC) which transmits (i) management and control frames with a lower frequency band by omnidirectional antennas and (ii) data and antenna training frames with millimeter waves by directional antennas. By doing so, the management and control problems of directional antennas are solved and high data rate can be achieved using 60 GHz radio. The asymmetric transmission range of the two frequency bands can be balanced by reducing the transmission power of 2.4/5 GHz so that it has equal coverage with the 60 GHz frequency band. Thus, ECM-MAC becomes a compelling, effective, and efficient solution to the directional communication problems of millimeter wave radio that maintains total backward compatibility with the present market leader of 2.4/5 GHz Wi-Fi technology.

D. Thesis Outline

The rest of the thesis work is organized as follows. In the following section, related works on 60 GHz multiband radio technology are reviewed. Section 3 presents the proposed novel multiband MAC protocol in detail. The performance of the proposed MAC is evaluated using two approaches a) Ad-hoc mode and b) Infrastructure mode and compared with Singh et al multi band MAC in Section 4. Finally, the thesis is concluded in Section 5.

II. Related Works

The enormous potential of the 60 GHz frequency 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. Specific standardization bodies include IEEE 802.15.3c [6], ECMA TC-48 [7] and IEEE 802.11ad [8]. Specific industry-led consortiums include Wireless HD [9] and WiGig [10].

IEEE introduced an 802.15.3c task group in 2005 and developed a millimeter wave-based alternative PHY layer for the existing IEEE 802.15.3 wireless personal area networks (WPANs), which supports high data rates of at least 1 Gbps. The IEEE 802.11ad task group was formed in January 2009. An amendment was proposed to modify both the PHY and MAC layers of the IEEE 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 IEEE 802.11 management planes. Both IEEE 802.15.3c and IEEE 802.11ad standards define the PHY and MAC layers for operation in the 60 GHz frequency band capable of multi-Gbps throughput. They can be effectively used for target applications of multi-Gbps local communications.

The European Computer Manufacturers Association (ECMA) is a non-profit association of technology developers, vendors, and users [7]. 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. 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 gigabit alliance (WiGig) [10] 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 Video Electronics Standards Association (VESA) have announced a cooperation agreement for multi-Gbps wireless networking and next-generation wireless display technology.

A. Design Considerations for MAC Protocols in 60 GHz Band

The serious issues such as high free space loss, gaseous absorption, lack of penetration and bending capability [3] 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 GHz and 5 GHz frequency spectra, but those protocols cannot be directly implemented because of the different physical and electromagnetic wave characteristics of the 60 GHz waves. Moreover, 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 [5]. 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.

1. Complicated Neighbor Discovery & 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 2-1, 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, and especially for the 60 GHz band it is infeasible, because its omnidirectional range is much more less as compared to its directional range, or the link would not be symmetrical.

2. Hidden node problem and new hidden node problem

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 2-1, 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 send 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.

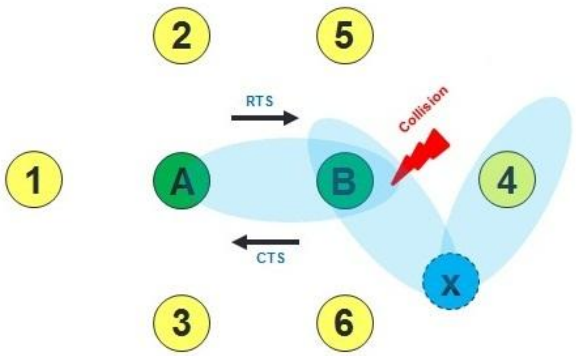


Figure 2-1: Deafness, hidden node problem and new hidden node problem.

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.

In Figure 3, 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 in 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.

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 MAC, layer because neighbors discovered using an omnidirectional antenna are generally not all the neighbors which could be in the range of that particular node using a directional antenna.

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 Figure 4. 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 & 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.

B. Existing Single Band MAC Protocols for 60 GHz band

This section focuses on the MAC protocols designed for 60 GHz mm wave communication. First general design principles of the proposed protocols are described then comparison and categorization of those protocols will be done in this section.

The author in [11] 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 ΔP, 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 the paper, 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 [12], [13]. 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 Target Request to Send (TRTS) to the PNC. TRTS has the address of Transmitter A, the PNC, and Receiver B. Then the PNC will send a Target Clear to Send (TCTS) 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 [14], 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 [15], 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.

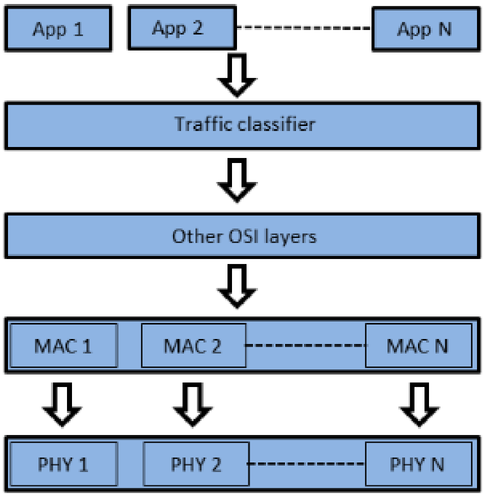
DLDR is used to transmit neighbor discovery-related packets, and DHDR is used for data transmission. One-hop neighbor discovery is performed using the angle of arrival (AOA) scheme, and one hop neighbor tracking is done by exchanging self-advertising packets. The link co-existence test is performed for 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 [16]. However, node mobility and neighbor discovery are not addressed in the simulation.

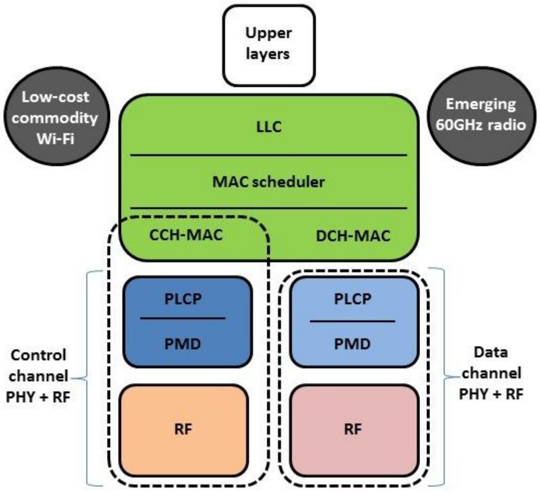
The necessary modification of IEEE802.15.3B has been proposed to be used as mm wave high data rate WPAN [17]. The author proposes automatic device discovery (ADD) and frame aggregation with unequal error protection (UEP) to achieve multi-Gbps communication using a super frame of a Piconet. Initially, 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 [18]. 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.

C. Existing Multi Band MAC Protocols for 60 GHz band

The target to achieve very high speed communication for transmitting uncompressed video has gained researchers' interest in developing multiband MAC protocols using both 2.4/5 GHz and 60 GHz bands. A multiband Wi-Fi system [19] is introduced as a usage model with design and implementation choices with pros and cons. Different ways to combine the 2.4/5 GHz VHF/UHF and 60 GHz radio bands and make them work together are discussed. Basically, three approaches to multiband MAC design are presented, which are multi-MAC multi-PHY, multi-MAC single-PHY, and single-MAC multi-PHY. Multi-MAC multi-PHY means different radio units are embedded in a device and they can work simultaneously. Multi-MAC multi-PHY is least challenging to design but needs comparatively high cost as it needs separate radio units. On the other hand, multi-MAC single-PHY is most complex to design among the three approaches as multiple MAC protocols use a single radio interface. Single-MAC multi-PHY is most preferred as a single MAC protocol can use multiple radio units simultaneously. Furthermore, authors advocate for single-MAC multi-PHY or multi-MAC multi-PHY in terms of implementation feasibility. A traffic classifier is also introduced in [19], as shown in Fig. 2-2 (a), which classifies traffic depending upon various attributes like real time/non-real time, high throughput/low throughput, voice/video, etc. The traffic requirement is passed on to the MAC layer, and is used for selecting a particular MAC protocol and PHY parameters.





(a) (b)

Figure 2-2: (a) Multiband Wi-Fi with a traffic classifier and (b) Dual-band protocol stack.

Low-cost Wi-Fi radios are used to control and coordinate scheduling/routing on a 60GHz directional multi-hop network in the dual-band architecture [20]. The low transmission range of the millimeter wave radio is extended by using multi-hop communication that has better spatial reuse capabilities due to effective scheduling and routing using the 2.4/5 GHz band. The authors consider a typical use case scenario of future applications in residential and office networks for transmitting multi-Gbps data. Each node is considered to be equipped with Wi-Fi radio and the 60 GHz radio as in Fig. 2-2 (b). A control channel (CCH) will be used by Wi-Fi radio and the data channel (DCH) will be implemented using the PHY and radio front-end (RF) of the 60 GHz band. The central coordinator manages and schedules operation of the 60 GHz network by broadcasting multi-hop routing information and spatial reuse opportunities to all the nodes. But, the 60 GHz communication with directional antennas has many opened issues [5] which are not addressed by this approach. The information broadcasted by a lower band does not contribute to the medium access for 60 GHz radio. The control and data plane use separate MAC and PHY, which make this protocol a multi-MAC multi-PHY scheme. That is the most costly design in terms of energy consumption and implementation cost [19]. However, since the control channel is designed on top of the point-coordination function (PCF) of IEEE 802.11, it has higher priority in transmission, and this algorithm makes devices interoperate with other 802.11 networks using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). The traffic classification approach [19] highlights the benefits of traffic splitting, as it reduces the overhead required for scheduling/routing on the 60GHz channel.

An energy-efficient multiband wireless LAN [21] at 60 GHz and 2.4/5 GHz was presented to reduce power consumption, in which a multiband MAC protocol was introduced. The main idea behind multi-band MAC is that nodes must use 60GHz whenever available and should avoid unnecessary peer station scanning when peers are out of range to save energy. An algorithm was also proposed in [21] to quickly detect the presence of peer stations at the 60 GHz band and avoid unnecessary energy waste in scanning or discovering when they are out of communication range. The protocol introduces a personal independent basic service set control point (PCP) to centrally control and arbitrate other stations (STAs) at the 60 GHz band. Furthermore, STAs periodically transmit the details of their 60 GHz band on a 2.4/5 GHz network as an IE frame. This IE assists in performing a multiband switch-over optimally by limiting the energy spent in 60GHz peer scanning as shown in Fig. 2-3. TBTT offset is the field in IE containing the observed duration of time in microseconds between the target beacon transmission time (TBTT) of the first band and the following TBTT in the second band.

In a multiband MAC protocol [21], all radio units are continuously powered on and periodically transmit a beacon by both the 60GHz and 2.4/5 GHz bands. Therefore, they can still waste large amounts of energy. This MAC can be classified as a multi-MAC multi-PHY protocol [19] which is comparatively less challenging to implement, but involves higher costs in terms of device manufacturing and energy consumption. Moreover, this approach uses the traditional antenna training and beam forming procedure, which does not take advantage of multi-radio devices. In the following section, we propose an energy-efficient multiband MAC which utilizes both frequency bands for antenna training and is energy-efficient compared to the conventional multiband MAC [21].

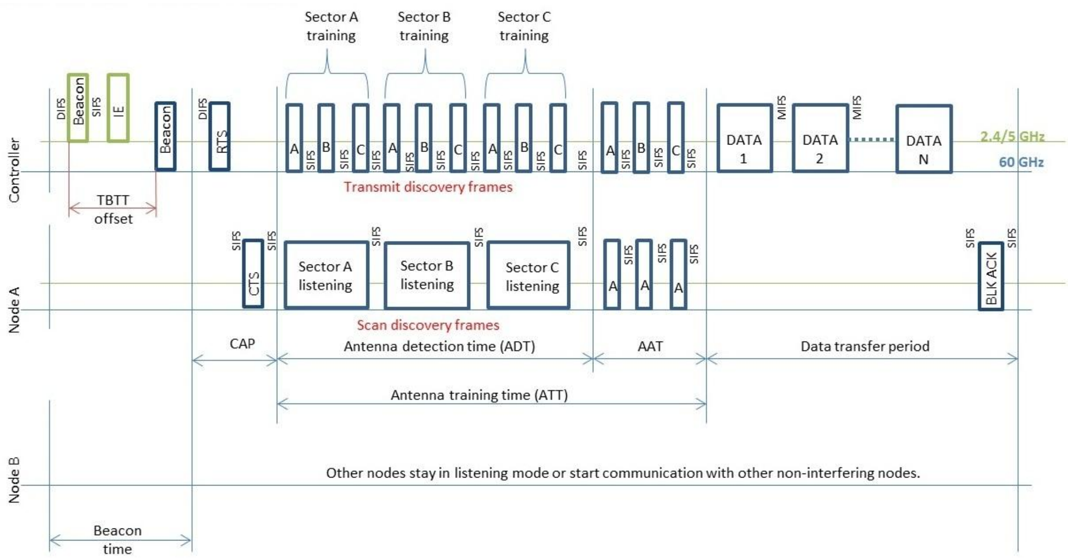


Figure 2-3: The multiband MAC protocol proposed by Singh et al. [8].

D. Comparison and Discussion

A list of MAC protocols proposed for mm wave high data rate communication is shown in Table 2-1. 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 neighbours. 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 neighbour discovery and antenna training procedure, device complexity also increases, which is reflected in Table 2-1. 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. In this way the MAC protocols can be classified 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.

Table 2-1: Comparison of MAC protocols for 60 GHz wireless LANs.

MAC protocol	Mode	Location tracking	LOS NLOS	Device complexity	Antenna	Mobility in simulation
ATIM window in 802.11 PSM [15]	Contention based	No	Both	Medium	Omni, directional antenna	Simulation not performed
DMAC-PDX [12]	Contention based	Polarization diversity scheme, Propagation delay	Both	High	Omni, Dual polarized smart antenna, Directional antenna	No
Directional CSMA/CA protocol [13]	Contention based	No	LOS	Medium	Phased array, Steerable antenna	No
Directional CSMA/CA protocol with spatial reuse [14]	Contention based	No	LOS	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	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	Medium	Omni, Directional antenna	No
Distributed MAC protocol [19]	Contention free	Hello message and wait for response	LOS	Medium	Electronic steerable antenna array	No

III. Proposed ECM-MAC protocol

The large potential of the 60 GHz band can be endured by overcoming the challenges it bring with directional antennas and small coverage. In this section, we propose an energy-efficient coordinated multiband MAC (ECM-MAC) that solves the problems associated with directional antennas such as deafness, hidden node problem and complicated neighbor discovery. ECM-MAC controls multiple physical layers for transmitting control and management frames at 2.4/5 GHz and antenna training and data frames at 60 GHz. ECM-MAC can be classified as single-MAC multi-PHY category. The proposed protocol is designed for a typical local area home communication with a scenario of applications for wireless transmission of uncompressed HD video and other bulk data within a range of 10 meters. The asymmetric transmission range between two frequency bands is balanced by reducing transmission power of 2.4/5 GHz radio so that both 60GHz and 2.4/5 GHz radios have equal coverage.

A. Traffic Classification

Various applications require different data rates and latency. Depending upon the required bandwidth, traffic can be classified and particular bands can be used for particular purposes as listed in Table 3-1. Transmitting 1080p uncompressed full HD video requires data rates of 2 to 4 Gbps, so the 60 GHz band should be used to transmit this data. On the other hand, browsing the Internet and sending emails require at most 1 Mbps, which can be fairly achieved by 2.4/5 GHz radio. The first step in our algorithm is classifying the types of traffic and appointing particular bands for them. The higher layers are assumed to classify the traffic and pass the information to the MAC layer which eventually selects the particular physical layer radio for transmission.

Table 3-1. Various applications and their data traffic.

Application	Data traffic	Required band
1080p uncompressed HD video	2-4 Gbps	60 GHz
1080i uncompressed HD video	1-2 Gbps	60 GHz
720p uncompressed video	500 Mbps – 1.5 Gbps	60 GHz
DVI	3.96 Gbps	60 GHz
VGA	1 – 3 Gbps	60 GHz
DVD video	3-10 Mbps	2.4/5 GHz
Compressed video	2-10 Mbps	2.4/5 GHz
Digital audio	128 Kbps – 25.5 Mbps	2.4/5 GHz
Voice encoding	64 Kbps	2.4/5 GHz
Other Internet applications	1 Mbps	2.4/5 GHz

B. Medium Access Control Procedure

After data traffic is properly classified at the upper layers, corresponding information is forwarded down to the MAC layer that controls the PHY layer for radio selection and data transmission. In this protocol, only one radio is turned on at a time, depending upon the information provided from the upper layers, and the 60 GHz band is only used for antenna training and transmission of multi-Gbps data. Since directional antennas are used for the 60 GHz band, 60 GHz transmissions are beam-formed, selecting a particular sector using all 2.4/5/60 GHz bands. As shown in Fig. 3-1, initially, the master controller node sends beacons using either 2.4/5 GHz radios omnidirectionally, which are received by all the nodes. Then association to the access point need to done by all devices which is performed using 2.4 GHz frequency band. Then, during the contention period, nodes send a request-to-send (RTS) frame to the controller or vice versa depending on the requirement that is acknowledged via the clear-to-send (CTS) frame. The RTS/CTS frames are used to reserve time slots for transmission in the data transfer period. This medium access request is also performed using 2.4/5 GHz radio. Furthermore, depending on the bandwidth requirement as mentioned, the MAC layer selects a particular radio band for data transmission. If the 2.4/5 GHz radio band is selected, then the data transmission is done traditionally like current Wi-Fi technology. Otherwise, nodes have to go through the antenna training procedure by selecting the 60 GHz band.

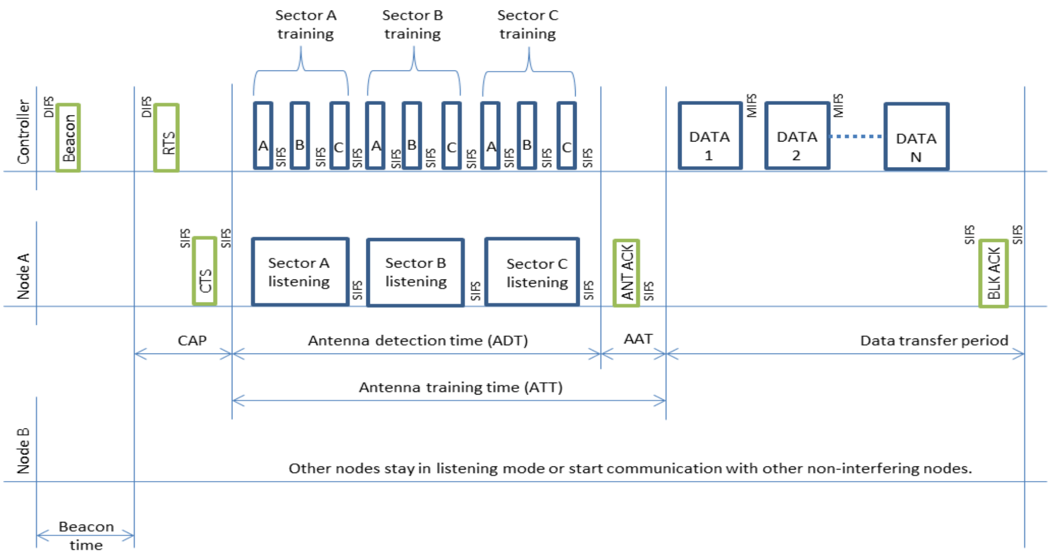


Figure 3-1: Proposed ECM-MAC Protocol.

C. Antenna Training Procedure

In the antenna training procedure, the nodes switch their radio to 60GHz with the previously-acquired timing information from the 2.4/5GHz beacon. Then, the antenna training frame (ATF) is transmitted using every sector in a round-robin fashion via the transmitter node, while the receiving node stays in listening mode for each sector. The receiving node stays in listening mode for a particular sector for the time the transmitting node transmits the ATF using all of its sectors in a rotational manner, as shown in Fig. 3-1, where each node has three directional antennas. This way, the receiving node receives the ATF transmitted from one or more sectors, compares the SNR of the received signal from each sector, and then selects the best pair of transmitting (TX) and receiving (RX) antenna sectors for 60 GHz directional transmission. The selected RX-TX sector pair information is transmitted back to the master controller using the 2.4/5 GHz band via the antenna acknowledgement (ANT ACK) frame (AAF).

D. Data Transmission and Acknowledgement

After sending back the AAF, data is transmitted using the 60 GHz band and the selected pair of RX-TX sectors. The data frames could be transmitted individually, or multiple data frames can be transmitted and a bulk acknowledgement (BLK-ACK) frame could be used to confirm delivery of multiple frames. An Acknowledgement (ACK) frame is sent back to inform transmitter about successful completion of data transfer. Acknowledgement frame is sent omnidirectionally using the 2.4/5 GHz band. Thus, utilizing one band at a time saves a noticeable amount of energy and significantly reduces the amount of antenna training time (ATT) compared to traditional antenna training procedure shown in Fig. 3-1.

E. Feasibility Analysis

Our analysis of the proposed MAC protocol uses the performance metrics of antenna training time (ATT), energy efficiency, and MAC efficiency. Fig. 3-2 shows the network configuration that we take into analysis. We consider two nodes in which the network controller with a large display is considered to be receiver and the other device is transmitting high definition video signals which require 60

GHz radio. Then, we evaluate the performance of the proposed MAC by comparing it with the conventional multiband wireless MAC [21] in the same scenario. The analytical results show that our MAC outperforms the conventional MAC. Any negative effects or overhead that degrade network performance are also observed.

Figure 3-2: Network topology for analysis.

1. Antenna Training Time

When we are dealing with the directional antenna in an ad-hoc network, the problems of antenna training and beam forming arise. In our proposal, we have implemented both the radios for effectively selecting the best sector pair for both transmitter and receiver. According to [21], the antenna training can be done using discovery frames after transmitting IE in the point-to-point device discovery period using only the 60 GHz band. Here, after traffic classification if the 60 GHz band is selected, the master device first transmits discovery frames in a rotational manner. Then another device, for instance Device A, stays in receiving mode for a particular sector for the period of time that the master device completes transmitting the discovery frames using all sectors. Again, Device A stays in listening mode using the next sector, while the master device sends a discovery frame using all its sectors in a rotational manner. After the completion of antenna detection, an AAF is sent by Device A by selecting the best TX-RX pair. After that, the same circular transmission procedure is repeated for this purpose where Device A now sends AAF using the selected sector and the master device listens rotationally. Finally, the best TX-RX pair is selected and the transmission of data is performed using mm waves, as in Fig. 3-3. Compared to this device discovery scheme, a previous scheme [22] does not compare the best signal, but instead Device A stops its rotation and sends back an antenna acknowledgement as soon as it receives the antenna training signal. The deficiency of this procedure is that the first signal it receives might be a reflected wave, or not the best signal it would have received using other sectors as in Fig. 3-3.

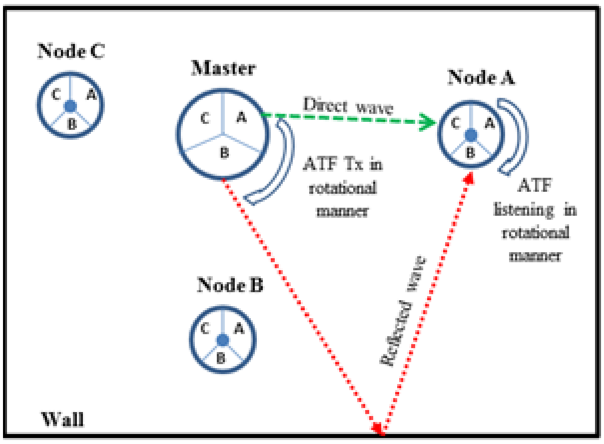


Figure 3-3: Direct and reflected wave selection for antenna training.

We divide the ATT into two parts, referred to as antenna detection time (ADT) and antenna acknowledgement time (AAT). In ADT, the receiving node receives ATF using all sectors in a circular fashion, compares the SNR of each received frame, and selects the best pair of the RX/TX antenna sector. Then, in AAT the receiving node sends back AAF, which contains information about the best sector pair. The antenna training time is denoted as ATT1 and ATT2 for the conventional protocol [21] and proposed protocol, respectively. N denotes the number of sectors. Then, ATT can be expressed as

$$ATT = ADT + AAT \tag{1}$$

$$ADT = N[N \times T_{ATF} + N \times SIFS] = N^2[T_{ATF} + SIFS] \tag{2}$$

$$AAT_1 = [N \times T_{AAF} + N \times SIFS] = N[T_{AAF} + SIFS] \tag{3}$$

$$AAT_2 = [T_{AAF} + SIFS] \tag{4}$$

$$ATT_1 = ADT + AAT_1 \tag{5}$$

$$ATT_2 = ADT + AAT_2 \tag{6}$$

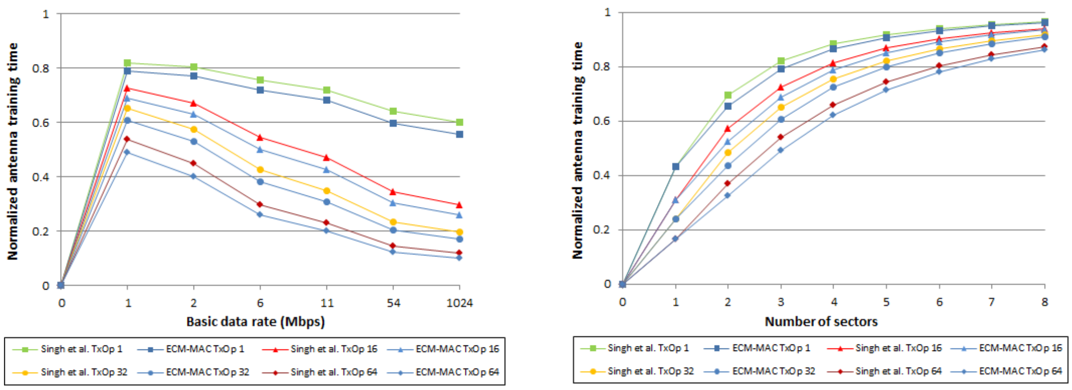
$$ATT_{SAVED} = \frac{ATT_1 - ATT_2}{ATT_1} = \frac{AAT_1 - AAT_2}{ATT_1} \tag{7}$$

Table 3-2. System parameters.

Parameter	Value
RTS packet	20 byte
CTS packet	14 byte
ATF packet	21 byte
AAF packet	22 byte
Data packet	1500 byte
Data Ack. packet	14 byte
Blk. Ack. packet	(14 + N*) byte
Basic data rate (2.4/5 GHz band)	1 Mbps
Channel data rate (2.4/5 GHz band)	1,6,11,54 Mbps
Channel data rate (60 GHz band)	1 Gbps
Basic data rate (60 GHz band)	1 Mbps
DIFS	50 µs
SIFS	10 µs
MIFS	2 µs
Slot Time	20 µs
Minimum Contention Window (CW)	32
MAC header	28 byte
PHY Header	24 byte

In Equations 2 and 3, N, T_{AAF} and T_{ATF} represent the number of sectors, the time required to transmit antenna acknowledgement frame and the time required to transmit antenna training frame, respectively. We consider three sectors in each node and use the parameters mentioned in Table 3-2. The system parameters presented in the table are taken for IEEE 802.11b and 802.15.3c network standards. In Table 2, N* gives the number of data packets sent before transmitting the bulk acknowledgement frame. With a basic data rate of 1 Mbps for 2.4/5 and 60 GHz for the transmission of control and management frames and 1 Gbps for the transmission of data using 60 GHz, we obtain 356 μs, or 17% of ATT saved in each beacon interval. This amount is almost 12% of the total frame time when we use 32 transmission opportunities (TXOP), i.e., 32 data packets are sent and a bulk acknowledgement (BLK-ACK) is provided at the time. So, our protocol significantly reduces the antenna detection time and chooses the best pair of RX-TX antenna sectors for high-speed directional communication.

The plot of normalized ATT_{SAVED} with respect to basic data rate and the number of sectors for various values of TXOP is shown in Fig 3-4 (a). Also it can be seen that as the number of sectors increases the ATT_{SAVED} decreases and the optimum result is obtained when we use two or three sectors in Fig 3-4 (b). The graph shows that our proposed ECM-MAC is superior to a Singh et al MAC [21].



(a) **(b)**

Figure 3-4: Normalised antenna training time for (a) varying basic data rate and (b) varying the number of sectors.

2. Energy Efficiency

Wireless networks always have an energy crunch and saving energy is always a great issue for researchers. As in any network, not all the devices are powerful enough to be connected to the main power supply. Further, there might be portable and mobile nodes with limited power supplies. Therefore, energy conservation should always be taken into consideration. In our protocol, we used dual radio that is never turned on simultaneously. So, using one radio at a time increases energy savings. Furthermore, reducing ATT further reduces energy consumption. The energy consumed for 2.4GHz radio, 60GHz radio, and idle radios can be represented in the following Equations (8) to (10), respectively. Furthermore, the total energy consumption is given by Equation (11).

$$E_{2.4} = E_{RTS} + E_{CTS} + E_{BEACON} + E_{ANTACK} + E_{ACK} \tag{8}$$

$$E_{60} = E_{ATF} + E_{DATA} \tag{9}$$

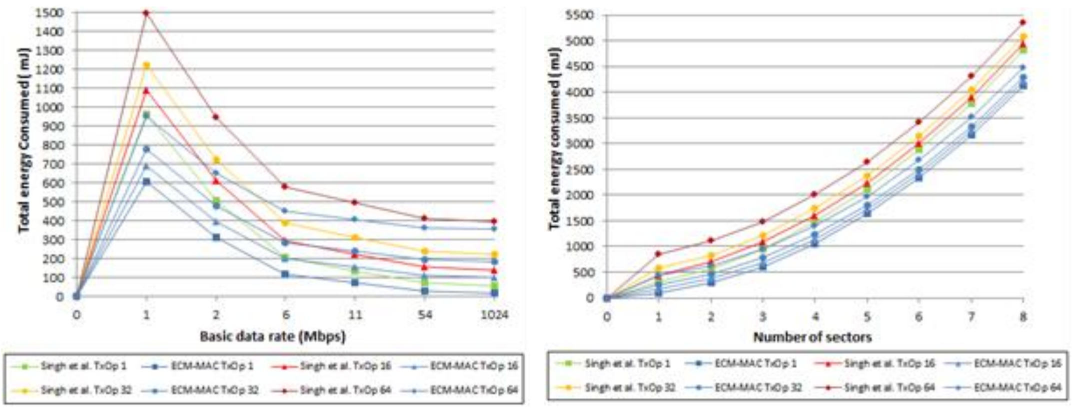
$$E_{IDLE} = P_{IDLE} \times T_{IDLE} \tag{10}$$

$$E_{TOTAL} = E_{2.4} + E_{60} + E_{IDLE} \tag{11}$$

Table 3-3. 2.4 and 60 GHz parameters for energy calculation.

Application	2.4 GHz Radio	60 GHz Radio
Distance (m)	10	10
Frequency (GHz)	2.4	60
Speed of light (m/s)	3.00E+08	3.00E+08
Free space loss (dB)	60.05	88.01302501
BER	1.00E-07	1.00E-07
Receiver sensitivity (dBm)	-81	-61
Fade margin (dB)	30	30
Gain of TX antenna (dBi)	0	17
Gain of RX antenna (dBi)	0	17
Transmit power (dBm)	9.05	23.01
Transmit power (mW)	8	200

Using Equations (8) to (11) above and the system parameters given in Table 3-3 [6], we can calculate the energy consumption of our dual-band MAC and a conventional MAC [21]. The results show that our protocol is 27% more energy-efficient than a conventional MAC. The plot of total energy consumed with respect to the number of sectors and basic data rate for various values of TXOP is shown in Fig. 3-5, where ECM-MAC has better results than the multi-band MAC proposed by Singh et al.



(a) **(b)**

Figure. 3-5. Total energy consumed for (a) varying basic data rate and (b) varing the number of sectors.

3. MAC Efficiency

MAC is a sub-layer of the data link layer of an open system interconnection (OSI) layered protocol model, which is responsible for efficiently accessing channels and making it possible for several nodes to share the medium. Efficiency of the MAC protocol can be evaluated by various metrics like delay, throughput, fairness, and power consumption. In this thesis work, MAC efficiency is defined as the ratio of the time required to transmit a MAC frame payload over the total time needed to transmit the entire MAC frame including protocol overhead. In this section, we have calculated the MAC efficiency by calculating the total MAC layer payload it carries with the help of other overhead. As our MAC protocol is multi-PHY single-MAC, which supports high-rate directional communication with additional ATF and AAF, we consider this additional overhead together with traditional RTS, CTS, DATA, and ACK. The structure of ATF and AAF is as shown in Fig. 3-6. ATF consists of a receiver address and transmitter address which are 6 bytes longer, similar to the RTS frame. Also the sector information which is 1 byte long is used to tell the receiver from which sector of the transmitting node it is receiving a signal. So, in one sector, the listening period of the receiver and transmitter has to send this ATF frame N times, where N is the number of sectors of the transmitting node. Each time the transmitter sends this frame, the particular sector information is attached in this ATF. Similarly, in an AAF, after selecting the best signal from the transmitter, the particular signal transmitting sector information is attached to the sector information TX slot, and the receiving sector information is attached in the sector information RX slot, which is sent using 2.4/5 GHz radio omnidirectionally. In this way, antenna training is done efficiently in the least possible time. MAC efficiency is calculated using Equation (12). Here $T_{MACPAYLOAD}$ is the time required to transmit the MAC frame payload, and $T_{OVERHEAD}$ is the time required to access the medium and other extra time overhead required for transmitting the actual data.

$$MAC_{EFFICIENCY} = \frac{T_{MACPAYLOAD}}{T_{MACPAYLOAD} + T_{OVERHEAD}} \qquad (12)$$

Calculating the RTS/CTS/ACK/ATF/AAF and DATA frames as shown in Fig. 3-6, we get the MAC efficiency. The plot of MAC efficiency for various values of a basic data rate and the number of sectors with respect to different values of TXOP is shown in Fig. 3-7. Compared to the conventional multiband MAC protocol [21], ECM-MAC significantly proves to be an efficient protocol. The efficiency of our MAC protocol evaluated by observing overhead required to transfer payloads 1500 bytes large is 13% greater for 32 TXOP. With the increase in the number of sectors, MAC efficiency decreases because of the increase in overhead for an antenna training procedure, which can be observed in Fig. 3-7.

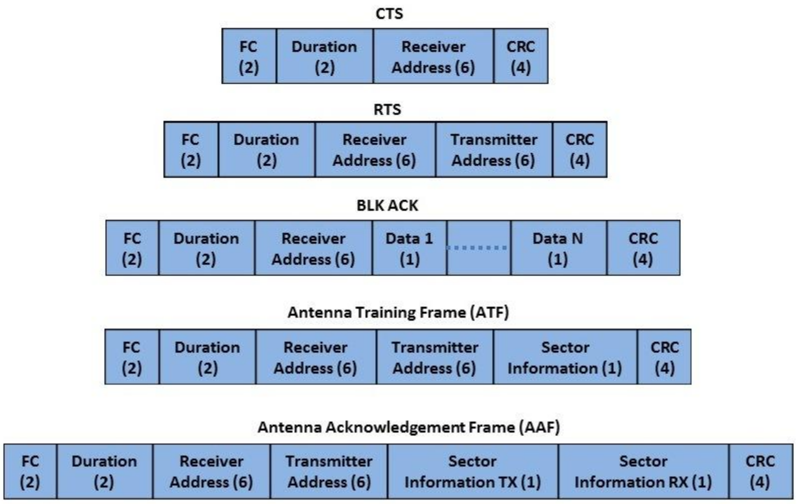
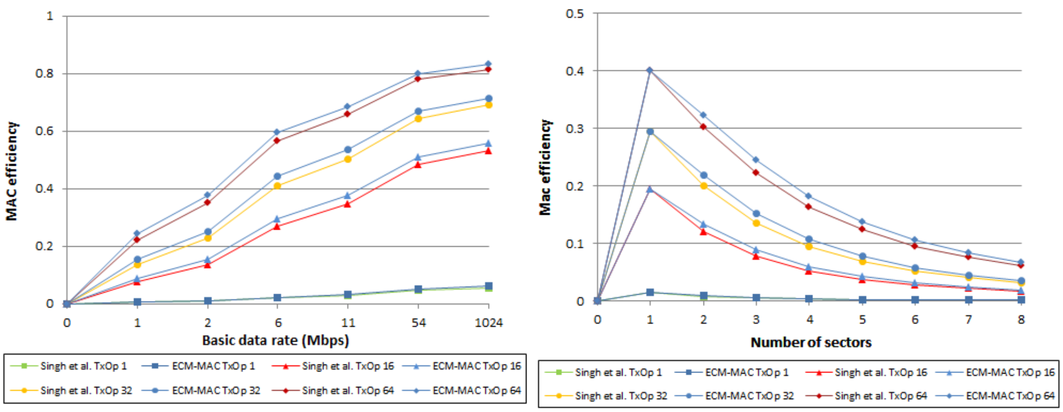


Figure 3-6 CTS, RTS, BLK ACK, ATF, and AAF frames.



(a) **(b)**

Fig. 3-7. MAC efficiency for (a) varying basic data rate and (b) varying the number of sectors.

IV. Performance Evaluation

A. Simulation Environment

In this section, the performance of ECM-MAC is evaluated via MATLAB simulation tool. We assume a scenario in which an access point with dual band capability controls the overall network. Fig. 4-1 shows the network topology for our simulation. In the topology, the central access point (AP) is the main controller of the network which has access to the broadband network provided by a service provider. The other nodes are transmitting various kinds of data like voice, video or internet packets.

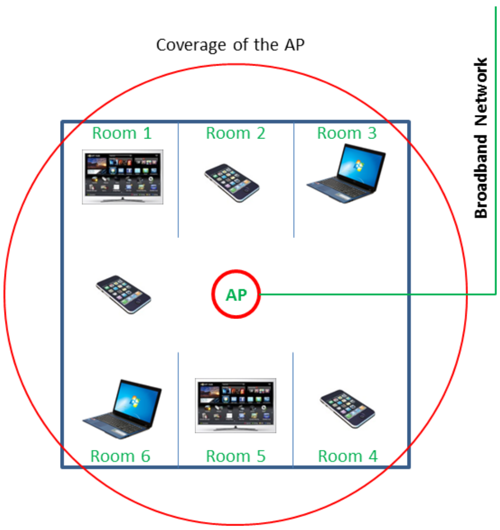


Figure 4-1: Network topology for simulation.

The communication procedure in this mode is different from that in ad hoc mode. The Superframe structure is given in Fig. 4-2. In the infrastructure mode of communication, after transmission of beacon frames, association to the AP has to be done by all the nodes. After being associated to the AP, devices reserve time slot for transmission of data. Both association and time slot request need contention-based access. If any node does not have data to be transmitted, time slot is not reserved. Thus, data transmission period may be variable.

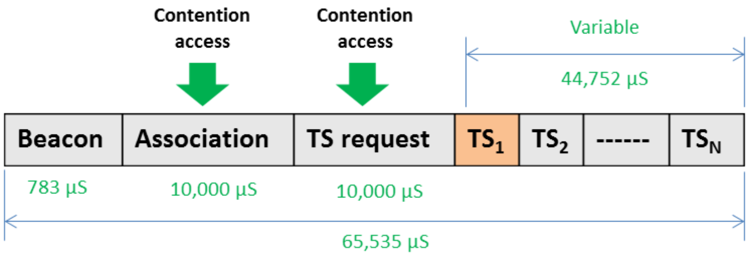


Figure 4-2: Superframe structure for ECM-MAC.

Table 4-1. Network parameters for simulation.

Parameter	Value
Number of nodes	50
Simulation area	10m x 10m
Distance between nodes	10m (random placement)
Radio frequency	2.4 & 60 GHz
2.4 GHz basic data rate	1 Mbps
2.4 GHz channel data rate	11 Mbps
60 GHz basic data rate	27.5 Mbps
60 GHz channel data rate	5 Gbps
Video packet size	95 Kbyte
Voice packet size	160 bits
Data packet size	1500 & 576 Bytes
Packet expiry time video	66 ms
Packet expiry time voice	150 ms
Packet expiry time data	200 ms
Simulation time	15 minutes

The performance of average delay and energy consumption per bit are evaluated. The metrics are observed by varying the number of nodes in the target network. Table 4-1 summarizes parameters for simulation. The proposed ECM-MAC and the conventional multiband wireless MAC [21] are simulated and compared to each other.

B. Simulation Results and Discussion

The plot of average end-to-end delay versus the number of nodes is shown in Fig. 4-3 (a). As shown in the figure, ECM-MAC has shorter average delay than Singh et al MAC. Because of efficient antenna training and communication procedure, ECM-MAC can achieve at least 14 % less delay as compared to Singh et al MAC. The average end-to-end delay is slightly increased with the increased number of nodes.

The plot of energy consumption per bit versus the number of nodes is shown in Fig. 4-3 (b). Energy consumed per bit is calculated by dividing total energy consumed during the simulation time by the total bits of frames transferred to the destination. ECM-MAC is at least 28% more energy-efficient than Singh et al MAC. This significant improvement results from the efficiently coordinated algorithm as well as using one radio at a time. The average consumed per bit is increased with the increased number of nodes as expected.

The plot of packet error rate (PER) vs. number of nodes is shown in figure 4-3 (c). PER is evaluated by calculating the number of packets dropped and dividing it by the total number of packets generated. Each generated packets has a packet generation timestamp. If a packet is not delivered to its destination within the packet expiry time it is dropped. As shown in the figure ECM-MAC has lower PER as compared to Singh et al. MAC because average delay of ECM-MAC is lower. As the numbers of nodes are increased PER also has an increasing trend.

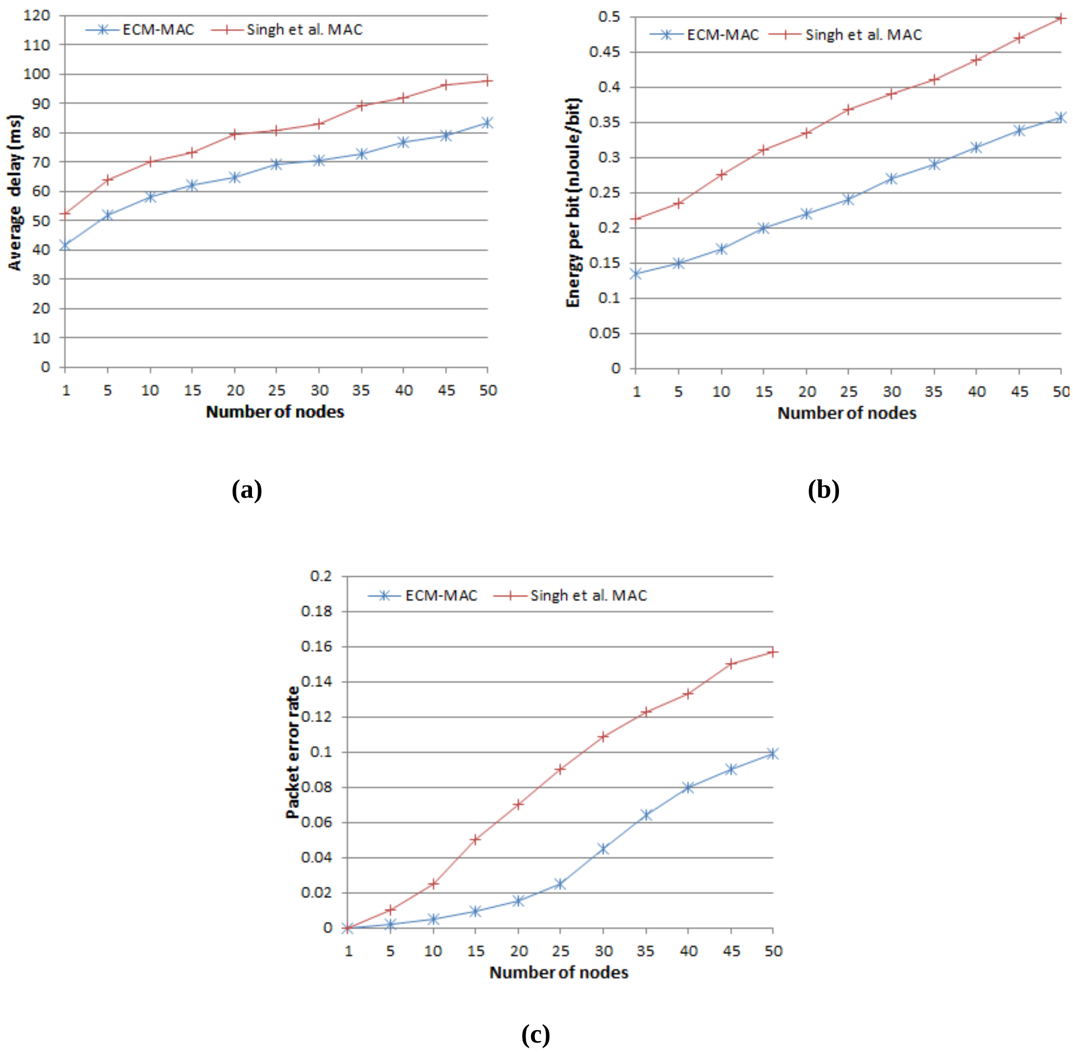


Figure 4-3: Simulation results: (a) Average delay (b) Energy per bit and (c) Packet error rate.

V. Conclusions and Future Works

Multi-Gbps networks are inevitably required in the near future to support high traffic demand for wireless HD video transmission and other multimedia traffic. Unlicensed 60 GHz bands can deliver such requirements, but its deficiency in providing large coverage and the usage of directional antennas make it complicated and rather difficult to implement. On the other hand, the 2.4/5 GHz radio, the market leader of current wireless networks, does not have sufficient bandwidth to carry such high traffic. So, in this thesis work we proposed a dual-band radio supporting both 60 GHz and 2.4/5 GHz bands, capable of carrying high data traffic rates within a room, with the features of co-existence and backward compatibility with a current Wi-Fi network. Our protocol utilizes both radio frequencies for achieving efficient data transmission in the least possible time. Furthermore, a remarkable amount of energy is saved by utilizing only one radio at a time. From the analysis, we can see that 27% of energy is saved, and 17% of the directional communication time is saved. The efficiency of our MAC protocol is evaluated by observing the overhead required to transfer payloads of 1500 bytes which is 13% larger for 32 TXOP. The simulation results also show that ECM-MAC outperforms Singh et al MAC in terms of average delay and energy consumption. This makes our protocol work reasonably well in a heterogeneous environment where not all nodes have dual radio capabilities.

In the future we would like to optimize the results obtained from the simulation by applying it in various environments. In present we have considered a scenario of typical home video network. We can create various scenarios like multi hop video transmission in stadium or surveillance and defense application and test the integrity of our proposed protocol.

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