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An Energy-Efficient Coordinated Multiband MAC Protocol for Backward-Compatible Multi-Gbps Wireless LANs

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Abstract

In this paper, an energy-efficient coordinated multiband medium access control (ECM-MAC) protocol for backward-compatible multi-Gbps wireless local area networks is proposed, which is capable of selecting the radio band based on required bandwidth for different applications. In ECM-MAC, the 2.4/5 GHz band with omnidirectional antenna is used for transmitting control, management, and low-rate data frames, and the 60 GHz band associated with directional antennas is used to transmit high-rate data frames at a multi-Gbps speed. In particular, antenna training is done efficiently, utilizing both 2.4/5 and 60 GHz radio bands selectively. The reduced antenna training time saves energy and shortens communication delay, and using one radio at a time further conserves energy. The simulation study shows that ECM-MAC consumes at least 28% less energy and reduces average packet delay by at least 14% by significantly reducing antenna training time, compared to the conventional protocol.

Keywords: Wireless LAN, 60 GHz, ISM band, multiband, multi-Gbps, directional antenna, MAC

1 Introduction

Applications like wireless transmission of uncompressed high definition (HD) video, bulk data transmission, and wireless data bus for high-definition multimedia interface and peripheral component interconnect express (PCI Express) cable replacements have raised the demand for spectrum bandwidth. The bandwidth of unlicensed industrial, scientific, and medical (ISM) bands of the 2.4 GHz and 5 GHz spectrum remains the same, while the number of users continues to increase. This spectrum deficiency problem creates interest in the millimeter wave ISM band working at a 60 GHz frequency range, with 7 GHz of available bandwidth capable of transmitting data at a higher throughput of 7 Gbps [1], [2]. This extremely high throughput 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 [3]. Furthermore, oxygen and other gaseous absorptions are very high for the frequency band. So, a 60 GHz network needs a directional antenna that compensates for the high loss with directional gain. Further, an antenna array with multiple antenna elements is realizable due to the small wavelength of 5 *mm*. Also the peak beam forming gain increases as the number of antennas increases, which give a 12 dB peak antenna gain when 16 element antenna arrays are used. Those 16 antenna elements can be packed into 1 cm^2 when adjacent antenna elements are separated by half the wavelength. This is extremely beneficial when considering small form factor devices [4].

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 procedure of neighbor discovery and efficient antenna training becomes very complicated, as directional antennas are not capable of either listening for or transmitting signals in all directions [5]. 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 60 GHz cannot acquire equivalent coverage even with directional antennas. Singh et al. proposed a multiband medium access control (MAC) [8] which leverages the benefits of both the 2.4/5 GHz and 60 GHz frequency bands. An information element (IE) frame is sent periodically on the lower frequency band to inform nodes about the status and information of the 60 GHz band. The IE facilitates in performing multiband switchover, optimally limiting the energy spent in 60 GHz peer scanning. However, the IE does not contribute to antenna training, which is a complex, tedious and energy-draining procedure. Above all, multiple beacons and control frames are transmitted in all directions by rotating the radiation pattern in different sectors to acquire full coverage [5]. Simultaneous operation of both radio units also increases energy consumption.

In this paper, we propose a novel MAC protocol named energy-efficient coordinated multiband MAC (ECM-MAC) which transmits (i) control, management, and low-rate data frames with a lower frequency band by omnidirectional antenna and (ii) high-rate data and antenna training frames with millimeter waves by directional antenna. By doing so, the control and management problems of directional antennas are solved, and a high data rate can be achieved using 60 GHz radio 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. Our simulation study shows that ECM-MAC outperforms the conventional multiband MAC in terms of energy consumption and average packet delay.

The rest of this paper is organized as follows. In the following section, related works on multiband radio technology are reviewed. Section 3 presents the proposed multiband MAC protocol in detail with respect to operational principles. In Section 4, the performance of ECM-MAC is evaluated and compared to the conventional MAC via extensive simulation. Finally, the paper is concluded in Section 5.

2 Related Works

The target of achieving very high speed communication for transmitting uncompressed video has increased research interest in developing multiband MAC protocols using both 2.4/5 GHz and 60 GHz bands. A multiband Wi-Fi system [6] was introduced as a usage model, with design and implementation choices that have both pros and cons. Different ways to combine the 2.4/5 GHz 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, where PHY stands for the physical layer. Multi-MAC–multi-PHY means different radio units are embedded in a device and can work simultaneously.

Multi-MAC–multi-PHY is the least challenging to design but brings a comparatively high cost because it needs separate radio units. On the other hand, multi-MAC–single-PHY is the most complex to design among the three approaches because multiple MAC protocols use a single radio interface. Single-MAC–multi-PHY is the most preferred because a single MAC protocol can use multiple radio units simultaneously. A traffic classifier was also introduced in [6], which classifies traffic at the application layer depending upon various attributes such as real-time/non–real-time, high-throughput/low-throughput, and voice/video. The traffic requirement is passed on to the MAC layer, and is used for selecting a particular MAC protocol and physical layer parameters.

In [7], low-cost Wi-Fi radios are used to control and coordinate scheduling/routing on a 60 GHz directional multi-hop network in the dual-band architecture. The low transmission range of the millimeter wave radio is extended by using multi-hop communication that has better spatial reuse capability due to effective scheduling and routing using the 2.4/5 GHz band. The typical-use scenarios of future applications in residential and office networks are considered for transmitting multi-gigabits per second (multi-Gbps) data. Each node is considered to be equipped with Wi-Fi radio and the 60 GHz radio as in Fig. 1. 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 60 GHz communication with directional antennas has many open issues [5] that are not addressed by this approach. Information broadcast 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 makes this protocol a multi-MAC–multi-PHY scheme. It is the most expensive design in terms of energy consumption and implementation cost [6]. 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 carrier sense multiple access with collision avoidance (CSMA/CA). The traffic classification approach [6] highlights the benefits of traffic splitting, because it reduces the overhead required for scheduling/routing on the 60 GHz channel.

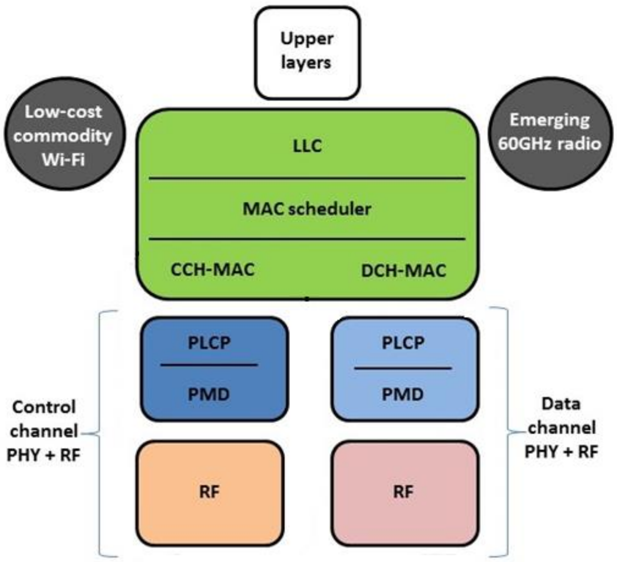


Fig. 1. Dual band protocol stacks

A multiband wireless local area network (LAN) [8] at 60 GHz and 2.4/5 GHz was presented to reduce power consumption, which is shown in Fig. 2. The main idea behind multiband MAC is that nodes must use 60 GHz whenever available and should avoid unnecessary peer station scanning when peers are out of range to save energy. An algorithm was also proposed [8] to quickly detect the presence of peer stations on 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 to centrally control and arbitrate other stations at the 60 GHz band. Furthermore, stations periodically transmit the details of their 60 GHz band on a 2.4/5 GHz network as the IE frame. Target beacon transmission time (TBTT) offset is the field in the IE containing the observed duration of time between the TBTT of the first band and the following TBTT in the second band.

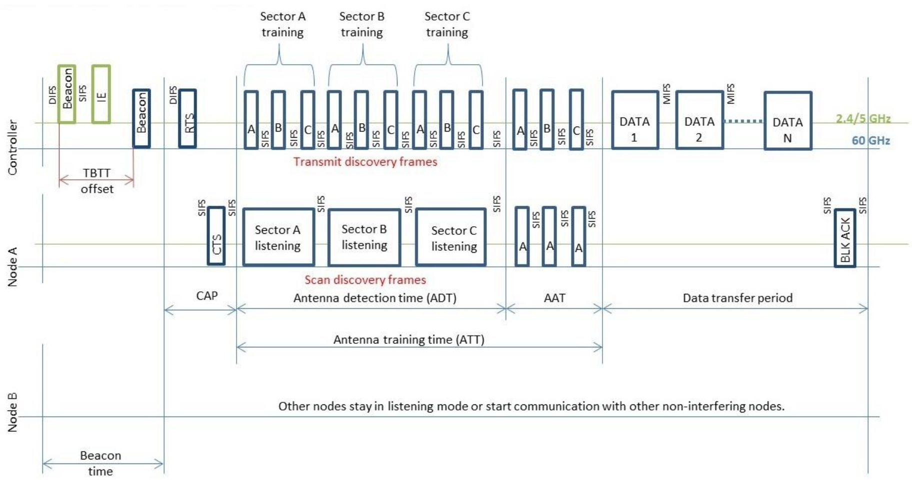


Fig. 2. The multiband MAC protocol proposed by Singh et al. [8]

In the multiband MAC protocol studied in [8], all radio units are continuously powered on, and periodically transmit a beacon on both the 60 GHz and 2.4/5 GHz bands, wasting large amount of energy. This MAC can be classified as a multi-MAC–multi-PHY protocol which is comparatively less challenging to implement but involves higher cost 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 that utilizes both frequency bands for antenna training.

3 Coordinated Multiband MAC Protocol

The potential of the 60 GHz band can be feasible by overcoming the challenges of directional antennas and small coverage. In this section, we propose an energy-efficient coordinated multiband MAC that solves the problems associated with directional antennas, such as deafness, the hidden node problem and complicated neighbor discovery. The proposed ECM-MAC controls multiple physical layers for transmitting not only control, management, and low-rate data frames at 2.4/5 GHz but also antenna training and high-rate data frames at 60 GHz. ECM-MAC can be included in the single-MAC–multi-PHY category. The proposed protocol is designed for 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 the 2.4/5 GHz radio so that both 60 GHz and 2.4/5 GHz radios have equal coverage.

3.1. 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. Transmitting uncompressed full HD video requires data rate of 2 to 4 Gbps and, thus, the 60 GHz band should be used. On the other hand, browsing the Internet and sending email usually requires several Mbps, which can be fairly achieved by 2.4/5 GHz radio. The first step in our algorithm is to classify the type of traffic and to appoint particular band for the traffic. The application layer classifies the traffic and the information is then used at the MAC layer for selecting the particular physical layer radio for transmission.

3.2. Medium Access Control

After data traffic is properly classified at the application layer, the corresponding information is forwarded to the MAC layer that controls the physical layers 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 layer, 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. As shown in Fig. 3, initially, the master controller node sends a beacon by using omnidirectional 2.4/5 GHz radio, which is received by all the nodes. The five kinds of frames of beacon, RTS, CTS, ANT ACK, and BLK ACK frames in Fig. 3 are transmitted by using 2.4/5 GHz radio. Then, association to the access point needs to be done by all devices, which is performed using the 2.4 GHz frequency band. Afterwards, during the contention period, the controller sends a request-to-send (RTS) frame to a node, or vice versa, depending on the requirement that is acknowledged via a clear-to-send (CTS) frame. The RTS/CTS frames are used to reserve time slots for transmission in the data transfer period, by using 2.4/5 GHz radio. Furthermore, depending on the bandwidth requirement, the MAC layer selects a particular radio band for data transmission. If the 2.4/5 GHz radio band is selected, data transmission is done traditionally, as with the current Wi-Fi technology; otherwise, the antenna training procedure is initiated by selecting the 60 GHz band.

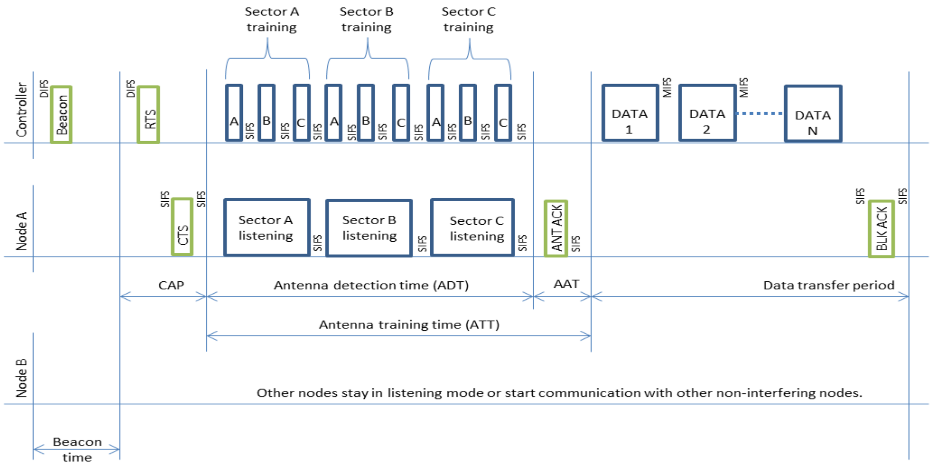


Fig. 3. The Proposed ECM-MAC protocol

3.3. Antenna Training Procedure

In the antenna training procedure, the nodes switch their radio to 60 GHz with the previously-acquired timing information from the 2.4/5 GHz beacon. Then, the antenna training frame (ATF) is transmitted using every sector in a round-robin fashion by 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 during the time the transmitting node transmits the ATF by using all of its sectors in a rotational manner, as shown in Fig. 3, where each node has three directional antennas. Tthe receiving node receives the ATF transmitted from one or more sectors, compares the signal-to-noise ratio (SNR) of the received signal at each sector, and then selects the best pair of transmitting (TX) and receiving (RX) antenna sectors for 60 GHz directional transmission. The information of the selected RX-TX sector pair is transmitted back to the master controller using the 2.4/5 GHz band via the antenna acknowledgement (ANT ACK) frame. In the conventional approach, however, the best signal is not taken into comparison, but the device stops its rotation and sends an ANT ACK as soon as it receives the antenna training signal [9].

3.4. Data Transmission and Acknowledgement

After sending the ANT ACK frame, data is transmitted via the selected pair of RX-TX sectors by using the 60 GHz band. The data frames can be transmitted individually, or multiple data frames can be transmitted with a bulk-acknowledgement frame that confirms the delivery of multiple frames. An acknowledgement frame informs the transmitter of the successful completion of data transfer. It is sent omnidirectionally by using the 2.4/5 GHz band. It should be noted hare that utilizing one band at a time saves a noticeable amount of energy.

4 Performance Evaluation

In this section, the performance of ECM-MAC is evaluated and compared to the conventional Singh et al. MAC [8] via extensive simulation. We describe the simulation environment and, then, the results and discussions will be presented.

4.1. Simulation Environment

We consider a wireless LAN in which an access point (AP) with multiband capability controls the overall network. In our performance study, 2.4 GHz and 60 GHz are taken into simulation. Fig. 4 shows the network configuration in which the central AP is main controller of the network, which has access to the broadband network of a service provider. Initially, the AP transmits a beacon. The nodes listening to the beacon send an association request to the AP. The AP confirms each device by sending an association response. After being associated with an AP, devices request time slots (TS) for transmission of data. Using the traffic information classified by the application layer, a particular radio is selected and a TS request is sent by a node to the AP by using a RTS frame. Now, if the required data rate is less than 11 Mbps, the node requests TS and informs the AP that it wants to transmit on the 2.4 GHz radio; otherwise, for data rate above 11 Mbps, the node requests TS on the 60 GHz radio band. The AP then allocates TS and sends back a TS response by using a CTS frame. Both the association and the TS request are carried out during the contention period by using the omnidirectional 2.4 GHz radio.

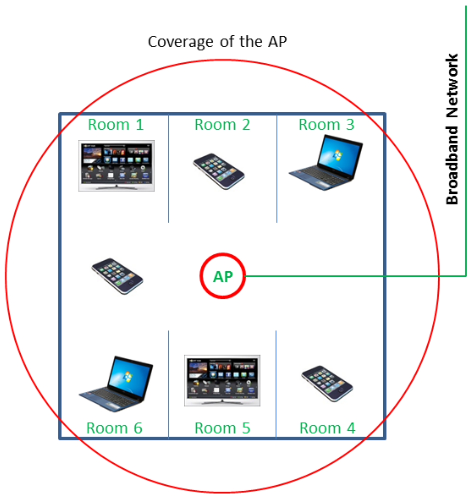


Fig. 4. Network configuration for simulation

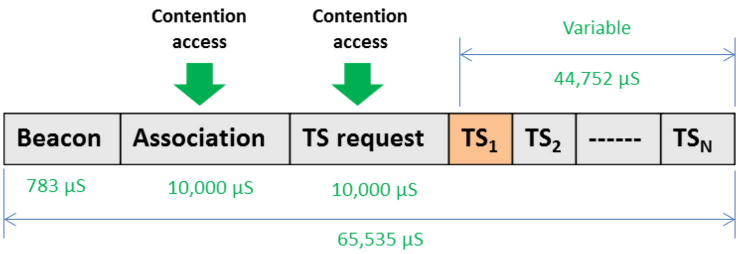


Fig. 5. Network configuration for simulation

Table 1. Simulation parameters

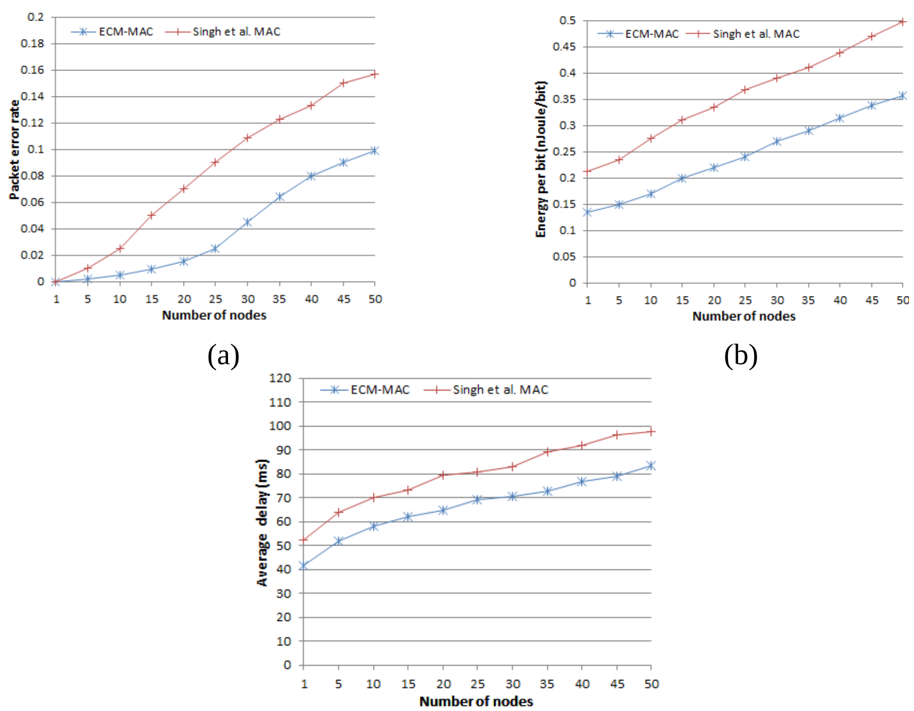
Parameter	Value
Number of nodes	50
Simulation area	10 m × 10 m
Radio frequency	2.4 and 60 GHz
2.4 GHz basic data rate	1 Mbps
2.4 GHz channel data rate	11 Mbps
60 GHz basic data rate	27.5 Mbps
60 GHz channel data rate	5 Gbps
Video packet size	95 Kbyte
Voice packet size	160 bits
Data packet size	1500 and 576 Bytes
Packet expiry time video	66 ms
Packet expiry time voice	150 ms
Packet expiry time data	200 ms
DIFS	50 µs
SIFS	10 µs
Receiver sensitivity (60 GHz)	-61 dBm
Receiver sensitivity (2.4 GHz)	-81 dBm
MAC header	28 bytes
PHY Header	24 bytes
Antenna gain TX/RX (60 GHz)	17 dBi
RTS packet	20 bytes
CTS packet	14 bytes
ATF packet	21 bytes
ANT ACK packet	22 bytes
Contention window minimum	8
Contention window maximum	1024
Simulation time	15 minutes

In Fig. 5, TS_1 is allocated by the AP for transmission on the 60 GHz band; 60 GHz transmission is always given the initial TS in the data transmission period of a superframe. With the 60 GHz radio, initially, antenna training is performed prior to data transmission in the allocated TS.

Voice, video and internet traffic are modeled for each node. We consider two nodes transmitting HD video at the rate of 1.5 Gbps with the 60 GHz radio. Then, voice traffic and internet data traffic are modeled for other nodes, which use the 2.4 GHz band. Each traffic model has a packet expiry time. If a generated packet is not delivered to the destination within the packet expiry time, it is dropped. The number of voice and internet nodes is increased at an interval of five during the simulation. The simulation parameters are summarized in Table I, many of which are come from the IEEE standard [10]. MATLAB version 12.0 is used for the platform of our simulation study. The transmission range of each node is considered to be 10 meters for both of the radios.

4.2. Simulation Results and Discussion

The simulation results are depicted in Fig. 6. The graph of the packet error rate (PER) versus the number of nodes is shown in Fig. 6(a). PER is evaluated by dividing the number of packets dropped by the total number of packets generated. Each generated packet has a packet generation timestamp. If the packet is not delivered to its destination within the packet expiry time, it is eventually dropped. As shown in the figure, ECM-MAC has lower PER compared to the Singh et al. MAC. When the number of nodes is small, there is little difference between the two protocols. But, as the number of nodes increases, the improvement is better and better by up to 60% as shown in Fig. 6(a). As the number of nodes increases, PER also increases proportionally.



(a) (b)

(c)

Fig.6. Simulation results: (a) packet error rate, (b) energy per bit, and (c) average delay

The graph of energy consumption per bit versus the number of nodes is shown in Fig. 6(b). Energy consumption per bit is calculated by dividing the total energy consumed during the simulation by the total number of bits in the frames transferred. ECM-MAC is at least 28% more energy-efficient than the Singh et al. MAC. This significant improvement results from the reduced antenna training time as well as using one radio at a time. As the number of nodes increases, the average energy consumption per bit increases as expected.

The graph of the average delay versus the number of nodes is shown in Fig. 6(c). The average delay is calculated by deducting the packet generation timestamp from the packet arrival timestamp and dividing the difference by the total number of packets delivered to the destination. As shown in the figure, ECM-MAC has a shorter average delay than the Singh et al. MAC. Because of the time-efficient antenna training and communication procedure, ECM-MAC can achieve at least 14% less delay compared to the Singh et al. MAC. The average delay slightly increases with the increased number of nodes.

5 Conclusions

Multi-Gbps networks are inevitably required to support high traffic demand for wireless HD video transmission and other multimedia traffic. Unlicensed 60 GHz bands can satisfy such requirements, but deficiency both in providing wide coverage and in using directional antennas makes the technology complicated and difficult to implement. Even though many MAC protocols have been studied for directional antenna systems, none of them are implemented in practical wireless LANs because of their complexity. On the other hand, the 2.4/5 GHz radio, the market leader for current wireless networks, does not have sufficient bandwidth to carry traffic comprising such huge amount of data. Our proposed ECM-MAC supports both 60 GHz and 2.4/5 GHz bands, which is capable of high-rate data traffic, with the features of co-existence and backward compatibility with a current Wi-Fi network. The performance study shows that ECM-MAC is superior to the conventional multiband MAC. Our future work is to implement the proposed ECM-MAC in a real scenario.

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