Exploring the Suitability of 60 GHz Radio for Building in-Home Networks

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ABSTRACT

60 GHz radio technology is highly promising since it can offer multi-Gbps data rate for short range wireless communication. Hence it is able to support in-home wireless multimedia applications such as high-definition video streaming, ultra high speed content downloads, etc. Hitherto, the main research efforts have been on 60 GHz physical layer design and channel model investigations. However, the unique properties of 60 GHz radio, *viz*, the use of directional antennas and link blockage problem impose new challenges for the higher layer protocol design. We explore the suitability of 60 GHz radio technology for in-home networks. In this paper we provide a comprehensive overview regarding medium access control related protocol design issues. Moreover, we also identify a number of directions which are helpful to develop the future architecture as well as technology to realize the grand vision of 60 GHz home networks.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

General Terms

Algorithm, Design, Performance

Keywords

60 GHz radio, in-home network, medium access control, performance analysis

1. INTRODUCTION

To cater to the emerging wireless multimedia applications like uncompressed high-definition (HD) video streaming, it is necessary to increase the data rate to the order of gigabits per second (Gbps). It is difficult to satisfy this requirement with the current wireless technologies. To alleviate the data rate bottleneck, researchers are exploring the unlicensed frequency band around 60 GHz. Abundant unlicensed bandwidth, up to 7 GHz, has been allocated worldwide for 60 GHz radio. Compared to other license-free bands, this is the largest contiguous block of radio spectrum ever allocated. Although 60 GHz radio is a newly emerging technology, the research on millimetre wave radio can be traced back to one hundred years, when J.C. Bose conducted experiments on wavelength from 2.5 cm or shorter to 5 mm (60 GHz radio) [6]. However, his pioneer research was way too early for any applications. It was not until World War II that the invention of radar brought practical uses for microwaves and millimetre wave radio. Traditionally 60 GHz radio technology was mainly used for military since it required expensive silicon technologies based on compound semiconductors such as InP and GaAs [13]. With the rapid development of CMOS technology, inexpensive and less power consuming 60 GHz radio is getting more attention. Thus 60 GHz radio technology is expected to boost wireless communication data rates to the order of multi-Gbps. Due to its substantial commercial potential, several international standardization organizations and industry-led efforts are also active with 60 GHz radio standardization, e.g. [2, 16, 1]. The principle usage for the 60 GHz radio technology is its applicability in networked future homes, where various types of multimedia applications are highly expected. 60 GHz consumer products are emerging in the market since 2009, such as wireless HDMI replacement solution. However, simply replacing a 10 m HDMI cable may not provide a bright future for the 60 GHz technology. Wireless HDMI replacement may be the killer application for 60 GHz radio, but it is not the only strength to motivate the research on 60 GHz radio. Lot of efforts are taking place to apply 60 GHz radio in a wider range of applications. For instance the IEEE 802.15.3 c standardization activity classifies 60 GHz radio usage models into five categories [10]: (1) uncompressed video streaming (2) multi uncompressed video streaming (3) office desktop (4) conference ad-hoc and (5) kiosk file-downloading. To achieve these goals,the issues like network formation, medium access, system coexistence, etc., need to be addressed. Hence, more grounded research work is expected to develop 60 GHz networking.

The nature of contributions of this work are three-folds: First, we provide a comprehensive overview regarding the medium access control (MAC)-related protocol design for enabling gigabits communication using 60 GHz radio technology in home networks. Secondly, we do not only provide a complete picture of the major research issues, but also

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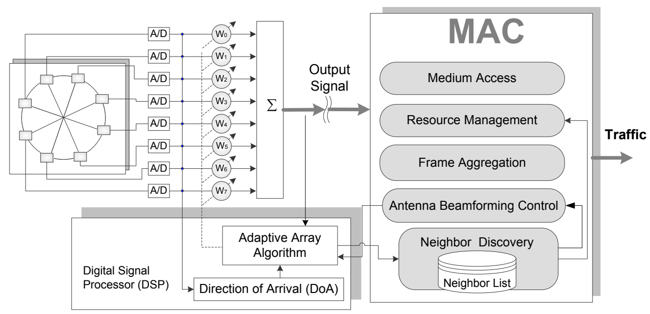

Figure 1: Functional blocks of MAC layer modules and interfaces with PHY layer.

briefly discuss the corresponding protocol design issues to address specified problems. We refer to the literature while discussing the uncovered issues and we provide our results therein. Third, we identify a number of interesting avenues for future investigations which are helpful in developing an architecture as well as technology to realize the grand vision of 60 GHz in-home networks.

The rest of the paper is organized as follows. In Section 2, we introduce the 60 GHz radio properties. In Section 3, we discuss the research challenges to enable 60 GHz in-home networks and corresponding solutions. In Section 4, we identify a number of directions for future research. Finally, we conclude the work in Section 5.

2. 60 GHZ RADIO PROPERTIES

60 GHz radio has some unique properties that make it substantially different from the radios at 2.4 GHz or 5 GHz frequency band. Compared to 2.4 GHz and 5 GHz radio, 60 GHz radio experiences higher path loss. To overcome high path loss, high-gain directional antennas are recommended in 60 GHz systems. If adaptive array antenna systems are used, the antenna pointing directions are electronically steerable. The advantages of directional antennas are as follows. Directional antennas can use the transmission power more efficiently compared to omni-directional antennas. Hence, using directional antennas achieve longer transmission range. The capacity of a radio link is directly related to the signal to interference plus noise ratio (SINR). Interference is mainly due to the transmissions from other close-by users. Using directional antennas, it is possible to reduce interference levels by nullifying signals from undesired directions. Hence the system capacity can be increased by the decreased level of interference. Moreover, the use of directional antennas can also enable spatial reuse capability. For indoor applications, the multi-path propagation causes delay spread, which limits the maximum bit rate due to inter symbol interference. Directional antennas suppress the multi-path dispersion by limiting the transmission power in undesired directions. Thus it results in smaller exposure area compared to omni-directional antennas. Due to the fundamental relationship between the signal wavelength and the antenna size, the wavelength of 60 GHz is of the order of millimetre, which makes it possible to design small sized antennas. Therefore, it is convenient to integrate 60 GHz featured transceivers with portable consumer electronic devices.

3. CHALLENGES AND PROPOSALS

Despite the tremendous bandwidth and the promising data rate that 60 GHz radio technology can offer, it is not straightforward to adopt 60 GHz radio based physical (PHY) layer for wireless personal area networks (WPANs). The unique properties of 60 GHz radio raise many new questions while designing the higher layer protocols. In this section, we identify the major research challenges to enable 60 GHz WPANs. To address these problems, it is essential to identify the impact of PHY layer on the performance of 60 GHz systems, for instance, the use of directional antennas, the propagation properties of 60 GHz radios. A MAC centric solution is proposed as shown in Fig. 1, which contains the major functional modules at the MAC layer and the interfaces with the PHY layer. Adaptive array antennas are considered in our work, which are capable to support antenna beamforming. Hence, the direction-related information of captured signals can be used at the MAC layer.

3.1 Directional Neighbor Discovery

A ND process allows in-range devices to link with each other and form a connected network. To set-up directional links, it is necessary for devices to know the direction of each others; hence the ND process needs to be operated in a directional way, which is also called as the directional ND (D-ND) process. In a D-ND process, advertisement messages are transmitted using directional antennas hence they are also called as directional advertisement (DA) messages. According to the reply mechanism, D-ND processes can be further classified as *one-way* D-ND and *handshake* based D-ND. One-way ND protocols require that each device periodically sends out DAs to announce its presence. Devices discover and update their neighbors' information by receiving DAs. For the handshake-based ND process, once a device receives a DA message from its neighbor, it provides an active response to the transmitter. According to the mechanism used to transmit the DAs, a D-ND process can be executed in two ways: *randomized D-ND* or *scanning based D-ND*. For a randomized D-ND process, devices randomly pick up a beam sector to transmit their DAs once they access the channel. For a scanning based D-ND process, if a device is in the transmitting state, it selects a beam sector to transmit its DA message, and moves (counter-)clockwise to transmit the next DA message in the next sector until it covers all the beam sectors. Several probabilistic models are proposed in [15] to model the one-way randomized D-ND processes. The handshake and scanning based D-ND was studied in [18]. D-ND in 60 GHz indoor wireless networks was investigated in [9]. The method is based on one-way randomized D-ND. The neighbor location discovery via direct path or non-direct path using linear and circular polarization and different responses to reflections with directional antennas operating in the 60 GHz band was emphasized in [17]. A detailed investigation on D-ND processes using different ND mechanisms and different antenna modes is provided in [4].

To analytically describe the performance of a D-ND process, except the ND mechanism and antenna mode, the selected radio propagation model and the neighborhood determination method also influence the obtained results. For instance, device i can be simply considered as the neighbor of device j if i is within the transmission range of j, which is called as link model-1(LM1). To guarantee a required transmission performance for a transmission pair (i, j), the SINR

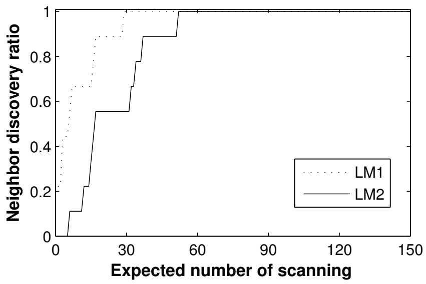

Figure 2: Influence of link model on the link probability and the ND ratio using 60 GHz radio with 1 GHz bandwidth, $PL_0 = 68$ dB, $I_L = 1.5$ dB, receiving sensitivity -72 dBm, SINR threshold 12 dBm, pathloss exponent 2.

should be higher than a certain threshold φ_{th}. Therefore, a link exists if,

$$10 \log \frac{P_r(\|i-j\|)}{N_0 + \sum_{k \in N, k \neq i} P_r(\|k-j\|)} - \varphi_{th} > 0$$

where $\sum_{k \in N, k \neq i} P_r(\|k-j\|)$ is the summation of the interfering powers and N_0 is the mean noise power. This is considered as link model-2 (LM2). To obtain some basic ideas of the influence of the adopted LM on the performance of a D-ND process, we wrote a simulator in MATLAB to study the scenarios. The set up is as follows: ten devices are uniformly distributed within a circular network with a radius of 5 m, and the target device is at the center of the network. Each device is equipped with a 6 element uniform circular antenna array system. The transmission probability is set to 0.2[1]. The ND ratios using different LMs after an one-way DO-ND process are depicted in Fig. 2. Although the same ND protocol is applied, LM1 and LM2 exhibit different ND performances due to different link models being used. Hence, to obtain a better performance of neighbor discovery, a link model which could describe the properties of 60 GHz radio more accurately is required. This aspect is not fully addressed in the current literature.

3.2 MAC Efficiency

MAC efficiency is a crucial factor to evaluate the performance of a MAC protocol. It can be simply defined as the proportion of the channel access time used for data communication within a system. Automatic repeat request (ARQ) at the MAC layer using Acknowledgment (ACK) and timeouts increases transmission reliability in error-prone channels. For instance, this mechanism is used in the IEEE 802.15.3 MAC [3], which is a well-known MAC protocol for high-rate WPANs. Especially, the IEEE 802.15.3c standardization group developed a MAC proposal for 60 GHz radio based on the IEEE 802.15.3 MAC. Since the data rate considered in the 60 GHz system is of the order of Gbps, the transmission overhead, in terms of delay, caused by the ACK and timeout mechanism severely impacts the capacity of 60 GHz systems.

[1]A slotted system is assumed in our simulation. Every N_b slots are grouped as a frame, where $N_b = 2\pi/\theta$ and θ is the antenna beamwidth. At the beginning of each frame, a device has a probability p_t to transmit and $1-p_t$ to receive. Once a device is in the transmitting state, it transmits one DA message in each slot.

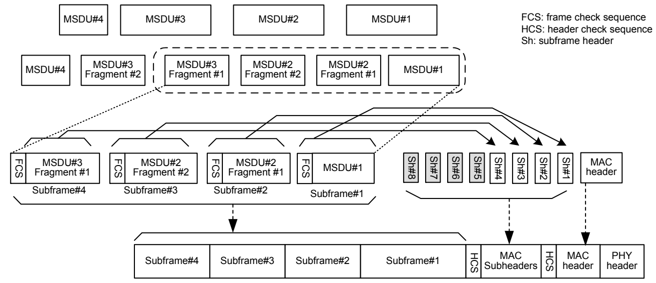

Figure 3: Standard frame aggregation

There are two ways to increase the capacity of 60 GHz systems. The first one is exploiting the spatial reuse capability using directional antennas. With the knowledge of the identities and directions of the neighbors, concurrent transmissions can be scheduled to increase system capacity. For instance in [5], a directional transmission scheduling algorithm and the corresponding resource management scheme based on IEEE 802.15.3 were proposed to schedule concurrent transmissions using directional antennas in 60 GHz WPANs. The second method uses the frame aggregation mechanism which can directly resolve the impact of overhead. Being different from the frame aggregation mechanism proposed in IEEE 802.11n, there are two frame aggregation mechanisms proposed in IEEE 802.15.3c for 60 GHz WPANs: standard frame aggregation and low latency frame aggregation [2]. The standard frame aggregation procedure at the transmitter side is illustrated in Fig 3. The transmitter maps a MAC service data unit onto a subframe payload once it receives it from the frame convergence sub-layer. Several subframes are grouped together as an aggregated frame. A subheader is created for each subframe to contain the necessary information that helps the receiver to retrieve the original data. All the subheaders are combined together to form the MAC subheader. Due to the aggregation, the standard frame aggregation mechanism can effectively improve system capacity when the channel quality is sufficiently high. However, the improved capacity comes at the price of the prolonged transmission delay. To cater to delay-sensitive applications, the low latency frame aggregation mechanism is derived to reduce the transmission delay. If the transmitter does not receive enough subframes, it just transmits empty subframes with zero length. In this way, the radio link between the transmitter and receiver is kept alive and the traffic arrival rate does not influence the subframes end-to-end transmission delay. In [4], we demonstrated the system delay as a function of $D \propto \mathbb{F}(\kappa_h, \kappa_l, n_{rt}, \gamma, l_h, l_p, n_s)$, where, κ_l and κ_h represent the modulation schemes for aggregated frame header and aggregated frame payload, respectively. l_h and l_p are the aggregated frame header length and payload length. n_{rt} is retransmission limit and n_s is the number of subframes in one aggregated frame. γ is the signal-to-noise ratio (SNR) value.

A MATLAB based simulator is constructed. We have used the 60 GHz PHY layer model specified in [11] in our simulation. QPSK is used as the modulation scheme for the transmission of data frames, $\pi/2$ BPSK is used as the basic/low rate modulation scheme. The LOS channel model

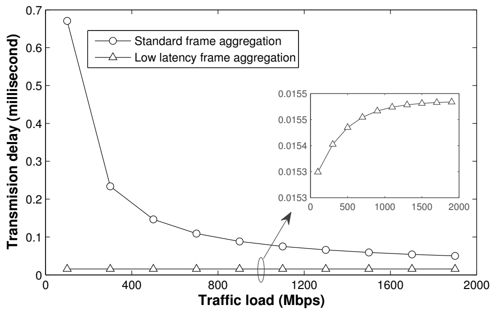

Figure 4: Performance comparison between standard and low latency frame aggregation, $n_{rt} = 3$, n_s=8, subframe length 1024 bytes and 7 dB SNR.

is adopted. The achievable data rates for using $\pi/2$ BPSK and QPSK are 1.61 Gbps and 3.23 Gbps, respectively. Each simulation result is the average value of the transmission of 10^4 aggregated frames. The transmission delay comparison between standard and low latency frame aggregation is shown in Fig. 4, which indicates that, the transmission delay is severely influenced by the traffic load if the standard frame aggregation mechanism is used. In comparison, the transmission delay obtained by using the low latency frame aggregation mechanism is not sensitive to the traffic load variations. For a detailed simulation setup we refer to [4]. The performance of frame aggregation is closely related to the channel quality, the number of aggregated subframes and also the subframe length. Hence, if the channel quality is not good enough, inappropriate parameter selection may degrade the performance of the frame aggregation mechanism. Thus it might be useful to investigate the self-adaptation of the frame aggregation according to the channel quality via cross-layer approaches.

3.3 Connectivity Maintenance

High-reliability is a crucial requirement for wireless communication to support multimedia applications. A direct index of reliability is the connectivity of a radio link. However, 60 GHz link is not so reliable even for one-hop 10 m connectivity, since in an indoor environment, a person moving around or any obstacle can easily block the radio link. Hence users have to carefully avoid crossing the linked devices. This is referred to as *link blockage*, which is a typical 60 GHz system problem. To support highly reliable 60 GHz networking, link blockage is definitely a hurdle to be resolved.

In [7], link blockage problem was resolved using system diversity in 60 GHz WLANs. The concept of virtual cellular networks and multiple receiving antennas was used to increase the beam path diversity at the receiver side, two antennas were considered in [7]. This concept increases the system complexity and signal processing difficulty but it is suitable for backbone based networks. A multi-hop solution is proposed to circumvent link blockage using relay devices in [14]. Thanks to the beam-forming capability of adaptive antenna array systems, it is capable of manually switching the antenna transmitting or receiving directions [12]. Hence, once the LOS link is blocked, a Non-LOS link can be used to maintain the connectivity as shown in Fig. 5. In [4], we propose a beam switching (BS) based mechanism to resolve

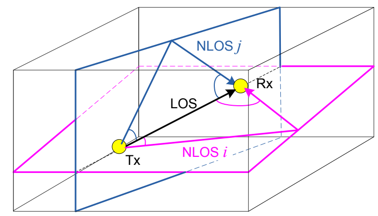

Figure 5: Illustration of the LOS beam path and the first order reflection beam paths in three-dimensional residential environment.

the link blockage problem. Targeting different usage models, the BS mechanisms are classified into two categories: instant decision based BS and environment learning based BS. The instant decision based BS refers to the mechanisms which only uses the currently available information to select backup links, for instance, the received SNR, direction of arrival (DoA) of a beam path, etc. The mechanism to select a backup link with the highest SNR is denoted as SNR-BS. The mechanism to select a NLOS link which is geometrically far away from the LOS link, but keeps the SNR as high as possible is denoted as DSNR-BS. The instant decision based BS is suitable for portable devices without fixed positions. The environment learning based BS uses the previous success/failure experience of BS to assist in selection of the backup beam path. The environment learning based BS is suitable for the usage model like uncompressed video streaming, in which devices like HDTV, Blu-ray player, are always stationed at fixed positions. The link visibility and the achievable system capacity have been assessed in a residential environment using different BS mechanisms. Combining the directional information of a beam path with the received SNR makes a better decision for BS.

3.4 System Coexistence

Applying 60 GHz radio for piconet based WPANs may incur the system coexistence issue. For a piconet based WPAN, it consists of a piconet controller (PNC) and a number of slave devices within the coverage range of the PNC. PNC periodically broadcasts beacons to provide timing information for the devices within its piconet [3]. Hence the coverage range of a piconet is decided by the transmission range of beacons. Due to the high path loss, high-speed 60 GHz transmission is only achieved within a short range (e.g. 10 m). Hence, it is possible for multiple 60 GHz WPANs to exist simultaneously within a certain area, for instance a meeting room or an exhibition hall. However, 60 GHz radio is prone to the variation in channel quality and the amount of interference. Especially interference from co-channel systems may easily degrade the performance of 60 GHz systems. Therefore, interference mitigation is an essential factor for the coexistence of WPANs to protect high-speed 60 GHz communications. Synchronization (sync) frame is proposed in [2] to mitigate co-channel interference (CCI). Sync frame provides a method to exchange timing information amongst independent piconets. The coverage range of a piconet is extended using surrounding slave devices to forward sync frames. Sync frames can be considered as copies of beacons, which contain the timing information of a piconet. For a device, if it receives a beacon or a sync frame from a piconet, it

Table 1: Parameters of different PHY Modes

	Modulation	Spreading Factor	Data rate
Mode 1	$\pi/2$ BPSK	1	1.61 Gbps
Mode 2	QPSK	1	3.23 Gbps
Mode 3	8PSK	1	4.86 Gbps
Mode 4	16QAM	1	6.48 Gbps

cannot become a PNC to establish its own piconet. In this way, the coverage range of a piconet can be extended and the channel quality of a target transmission pair can be well protected. An investigation was done to examine the performance of using sync frame within coexisting WPANs [4]. The importance of beacon/sync frame range in WPANs lies in the competition for throughput between different piconets in the same area. Hence, the beacon and sync frame range is a crucial factor to decide the achievable piconet capacity since the spatial reuse capability (the number of coexisting piconets in a certain area) is inversely proportional to the amount of CCI. To obtain the relationship between beacon and sync frame range with CCI, special treatment has been given in the proposed theoretical model, in which, the log-normal radio propagation model is used to model the accumulated CCI in each piconet. To demonstrate the performance of sync frames, we deployed a network with 100 devices within a circular network with radius of $30\,\mathrm{m}^2$. The channel model used amongst the devices is of LOS in nature. The target receiver is in the middle of the network. The target transmitter is located d_t m away from the target receiver. The positions of the other 98 devices are uniformly distributed within the circular area. Two network topology formation mechanisms are considered in the simulation:

- Network formation without using sync frames: After a device is generated, it associates with the closest PNC that it can reach. If there is no surrounding PNC, it becomes a PNC and initiates its own piconet.
- Network formation using sync frames: After a device is generated, it associates with the closest PNC. If this device is not within the beacon range of any piconets and it receives sync frames from the relaying devices, it associates with the closest relaying device. If this device is not within the coverage range of any beacon or sync frames, it becomes a PNC.

The CCI level ζ and the selected MCS κ_i determine the achievable BER e_{κ_i} at the target link as $e_{\kappa_i} = f_{\kappa_i}(\zeta)$. The mapping relation $f_{\kappa_i}(.)$ presented in [11] is adopted in this work. For a memoryless channel, the bit errors can be assumed as non-correlated and they are uniformly distributed within a packet. Under this assumption, the resultant PER is expressed as $P_e^{\kappa_i}(l) = 1 - (1 - e_{\kappa_i})^l$, where l is the frame length (in bits). Therefore, the system throughput without considering any ARQ technique can be approximated as $C = (1 - \eta)R_{\kappa_i}(1 - P_e^{\kappa_i}(l))$, where R_{κ_i} is the transmission data rate using MCS κ_i. The achievable data rate using different modulation scheme is listed in Table 1. η is the proportion of overhead, $\eta = \frac{t_o}{l/R_{\kappa_i} + t_o}$, where t_o is the time duration for overhead which includes the packet preamble, packet header, and minimum inter-frame spacing length.

[2]According to the prediction of WWRF meeting, seven trillion wireless devices serving seven billion people by 2017, which means there will be 1000 wireless devices provide services for one person [8].

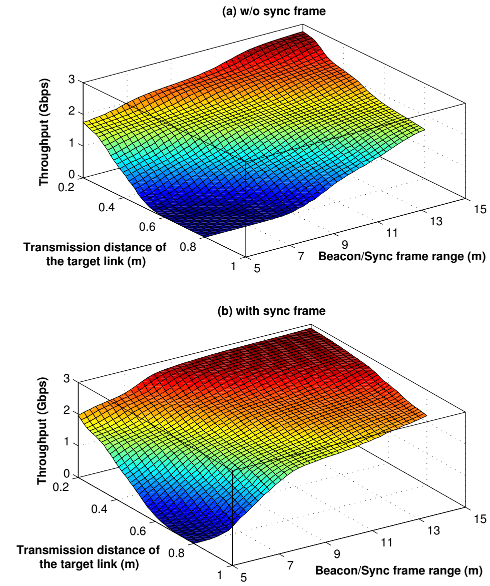

Figure 6: Relationship between the target transmission distance, beacon range, and the achievable target link capacity.

The relationship among the target transmission distance d_t, beacon range, and the achievable target link capacity are depicted as 3-dimensional plots in Fig. 6, which provides an overview of the performance with and without sync frames. It is observed that communication within a single WPAN can be effectively protected from other coexisting WPANs using sync frames. When the beacon/sync frame range is fixed, using sync frames can dramatically increase the system capacity.

4. DIRECTIONS FOR FUTURE WORK

Based on our investigation so far, it has been shown that 60 GHz radio could be used in short-range high data rate wireless communication. However, we believe that it is still a long way to adopt 60 GHz radio in future home networks, which is also envisioned with ambient intelligence. Therefore, we raise here a few issues that are worthy of investigation.

(1) *Cross-layer optimization*: Protocol-wise solutions for 60 GHz networks should be service-oriented. Different applications have different requirements regarding transmission data rate, channel quality, and have different QoS constraints. Hence it is an interesting aspect to investigate protocol-wise adaptation according to the delivered services via cross-layer optimization approach. For instance, a beam switching mechanism is discussed in this work to resolve the LOS link blockage problem. However, it is possible that the alternative NLOS link cannot provide sufficient link budget for high speed communication. For the sake of reliability, it is necessary to adjust QoS requirements according to the current status of the channel. For example, to adapt uncompressed video stream to compressed video stream, this

is a resource management issue involving cross-layer optimization.

(2) *Coexistence of multiple standards*: To facilitate the development of 60 GHz radio technology propelled by industry, as we mentioned before, a number of non-profit international standardization groups and industry-led efforts have come up to unify and standardize the use of 60 GHz radio technology. It is expected that many 60 GHz products featured by different industry standards will reach the market. Thus there is a serious concern on their capacity to co-exist and interoperate.

(3) *Cooperation with multiple technologies*: In future networked components, including portable personal consumer electronic devices, are envisaged to be capable of supporting multi-technology with multiple-interfaces. Hence it is worth investigating how to maximize the 60 GHz system capability by acquiring the assistance and cooperation with other technologies. For instance, assume that a device has multiple radio interfaces, once the 60 GHz radio connectivity is blocked, the device may easily switch to a low frequency band for instance 2.4 or 5 GHz, to maintain the connectivity. Moreover, the combination of 60 GHz radio and radio-over-fiber technology may solve the mobility and handover hurdles which cannot be easily addressed by 60 GHz radio alone.

5. CONCLUSION

60 GHz radio is a very attractive technology for short-range wireless communication, meanwhile it also has some serious limitations. Our work is motivated to provide an overview of MAC-centric framework to enable high performance communication in home networks using 60 GHz radio technology. We addressed a number of issues, like neighbor discovery, frame aggregation, connectivity maintenance and system coexistence. We believe that given sophisticated designs, it is suitable to apply 60 GHz radio for in-home networks to support high capacity and highly reliable communication. We categorically state that there are many unresolved challenges to make future 60 GHz in-home networks.

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