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Pengfei Xia
Samsung Electronics

Xiangping Qin
xqin@siu.edu

Huaning Niu
Samsung Electronics

Harkirat Singh
Samsung Electronics

Huairong Shao
Samsung Electronics

See next page for additional authors

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Authors
Pengfei Xia, Xiangping Qin, Huaning Niu, Harkirat Singh, Huairong Shao, Jisung Oh, Chang Yeul Kweon, Seong Soo Kim, Su Khiong Yong, and Chiu Ngo

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Pengfei Xia* , Xiangping Qin*, Huaning Niu*, Harkirat Singh*, Huairong Shao*,
Jisung Oh†, Chang Yeul Kweon†, Seong Soo Kim†, Su Khiong Yong*, Chiu Ngo*
Samsung Electronics
*75 W Plumeria Drive, San Jose, CA 95134, USA
†416 Maetan-3Dong, Suwon, Kyungki-Do, Korea 443-742.

***Abstract*—In this paper, we discuss multi-gigabits per second wireless networks in the 60GHz millimeter wave frequency band. Despite the large unlicensed bandwidth offered by the 60GHz frequency band, severe technical challenges exist towards making multi-Gbps a reality. We discuss the challenges in three different layers: PHY, MAC and the application layers. We also discuss some important technologies in overcoming these challenges, including antenna array beamforming, baseband modulation, data aggregation. The worldwide 60GHz regulatory and the ongoing standardization efforts are reviewed as well.**

I. Introduction and Potential Applications

Wireless communication in the 60GHz millimeter wave (mm-wave) communications is getting increasing attention as a promising candidate in supporting multi-gigabits per second (Gbps) throughput nowadays. Major motivation for using the 60GHz band is that a very large block of unlicensed spectrum is available worldwide. For example, in the US, 7GHz unlicensed band ranging from 57GHz to 64GHz is available, while similar channel planning can be found for other countries around the world [9]. Table I shows a brief frequency planning in major consumer markets around the world.

Multi-Gbps mm-wave communications can be utilized by many consumer electronics (CE) applications, e.g., uncompressed video streaming. The High Definition Multimedia Interface /Digital Video Interface (HDMI/DVI) cable from the STB/DVD player to High Definition Television (HDTV) can be replaced by mm-wave wireless. Required data throughput varies from several hundred Mbps to a few Gbps, depending on the overall resolution. For current 1080p HDTV with a resolution of 1920×1080 and a refresh rate of 60 Hz, the required data throughput turns out to be approximately 3 Gbps for active video data only, and 4.5 Gbps when horizontal and vertical blanking areas with TMDS (Transition Minimized Differential Signaling) encoding included. Uncompressed video streaming is appealing also because of its extremely low communication delay as complicated, and time-consuming video encoding/decoding can be spared.

High speed file transfer is another important application for Gbps mm-wave communications. A number of data/file transfer applications have been envisioned, such as video downloading from a kiosk, mobile distributed computing, wireless docking station, wireless gigabit Ethernet and others. In the video kiosk scenario, users can quickly download movies and music from kiosk stations to portable devices. Figure II shows the general IEEE 802.15.3c user requirement parameters for different applications of 60GHz wireless networks.

Standardization in the 60GHz wireless networks is being carried out by several different international organizations. Supported by LG, Matsushita, NEC, Samsung, Sony, Toshiba and SiBEAM, the upcoming digital interface WirelessHD standard is intended to enable high-definition audio video (A/V) streaming and high-speed content transmission for consumer electronics (CE) devices, with specification 1.0 to be released in late 2007. IEEE 802.15.3c Task Group is also defining a mm-wave-based alternative physical layer for the existing 802.15.3 Wireless Personal Area Network (WPAN) Standard, which will allow data rate as high as 2 Gbps. In the meantime, another international organization ECMA (European Computer Manufacturers Association) International is also working on a mm-wave wireless technology in its TC32-TG20 group, targeted at supporting both video streaming and file transfer applications.

In this paper, we present interesting challenges and important technologies for the multi-Gbps wireless networks in the 60GHz frequency band, from the perspectives of physical (PHY) layer, MAC layer and application (APP) layer. The paper is organized as follows: challenges and technologies for 60GHz wireless networks in the PHY layer are discussed in Section II. Following that, MAC layer and APP layer challenges and technologies are presented in Section III and Section IV respectively. Finally the paper is concluded in Section V.

II. Challenges and Technologies in PHY Layer

A. Radio Frequency Challenges

Radio frequency devices pose the fundamental challenge for communication circuits in mm-wave home networks. Existing candidates of RF technologies include GaAs (Gallium Arsenide), SiGe (Silicon Germanium), CMOS (Complementary Metal Oxide Semiconductor) among others. We here mainly discuss the technology of GaAs and CMOS. GaAs in general is superior to silicon in terms of certain electronic properties. In particular, GaAs has a higher saturated electron velocity and higher electron mobility, allowing GaAs devices to function well at frequencies even in excess of 250 GHz. Also, GaAs

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TABLE I
WORLDWIDE REGULATORY FOR UNLICENSED 60GHZ BAND

Region	Band (GHz)	max. Tx Power (mW)	EIRP (dBm)	max. Antenna Gain (dBi)
USA/Canada	57-64	500	43 (max)	n/a
Europe	57-66	20	57 (max)	37
Japan	59-66	10	n/a	47
Korea	57-64	10	n/a	17
Australia	59.4-62.9	10	n/a	n/a

TABLE II
USER REQUIREMENT PARAMETERS

Usage case	Data Rate	Range	Traffic Type	Symmetry	Mobility	Channel Model	MSDU size	BER	Delay and Jitter
Uncompressed HD video	0.5-8 Gbps	10-20m for conference room; $<$ 10m for home	isochronous	asymmetric	no	indoor LOS/NLOS	very large	$< 10^{-9}$	$D < 10$ ms; $J < 1$ ms
Audio	$<$ 40Mbps	10-20m for conference room; $<$ 10m for home	isochronous	asymmetric	yes	indoor LOS/NLOS	$<$ 5K bytes	$< 10^{-7}$	$D < 10$ ms; $J < 1$ ms
MPEG2 video	$<$ 40Mbps	$<$ 10m for home	asynchronous	asymmetric	yes	indoor outdoor LOS/NLOS	220 bytes	$< 10^{-9}$	$D < 1$ s; $J < 100$ ms
One way gaming	$0.05 - 1$Gbps	$<$ 10m	isochronous	asymmetric	no	indoor LOS/NLOS	n/a	$< 10^{-9}$	$D < 10$ ms; $J < 1$ ms
Gaming between 2 devices	$0.05 - 1$Gbps	$<$ 10m	isochronous	symmetric	no	indoor outdoor LOS/NLOS	n/a	$< 10^{-9}$	$D < 10$ ms; $J < 1$ ms
Wireless G-ethernet data	$0.5 - 1$Gbps	10-20m for conference room; $<$ 10m for home	asynchronous	symmetric	no	indoor outdoor LOS/NLOS	1518 bytes	$< 10^{-6}$	$D < 3$ s; $J < 500$ ms
File transfer between 2 devices	$0.5 - 1$Gbps	$<$ 10m	asynchronous	symmetric	no	indoor outdoor LOS/NLOS	1500 bytes	$< 10^{-6}$	$D < 3$ s; $J < 500$ ms

devices yield less noise than silicon devices when operated at high frequencies. Furthermore, GaAs devices can be operated at higher power levels than the equivalent silicon device because they have higher breakdown voltages. However, GaAs devices generally incur a large cost, and is not very desirable for consumer electronics.

Although very challenging, CMOS technology is becoming increasingly popular for mm-wave devices, as it promises significantly lower system cost and power consumption. The fundamental challenge for mm-wave RF in CMOS technology is the absence of CAD tools as well as accurate models for various active and passive building blocks of the RF circuitry. In particular, as the frequency approaches mm-wave frequency band, novel design methods incorporating microwave techniques have to be employed to deal with new challenges in the mm-wave paradigm. Those standard transceiver building blocks such as the low noise amplifier (LNA), voltage controlled oscillator (VCO), phase-locked loop (PLL), mixer, and power amplifier, warrant close re-investigation and careful re-design in the context of mm-wave frequency band.

Existing models for CMOS transistors are largely unsubstantiated at the mm-wave frequency. For this reason, accurate modeling of various active and passive blocks is required for efficient circuit design. Furthermore, as we are approaching mm-wave frequency, it becomes possible to integrate many otherwise off-chip components, such as filters, switches, networks and array of antennas, directly in the whole package. Pioneering work in CMOS RF for mm-wave applications has been done in [1] and the references therein.

B. Directional Transmission: Bridging 60GHz Wireless Link

One of the major challenges for mm-wave Gbps communications is the poor link budget, as radio signal propagating in the mm-wave frequency band experiences significant path loss, reflection loss, multi-path, and other degradation. In addition,

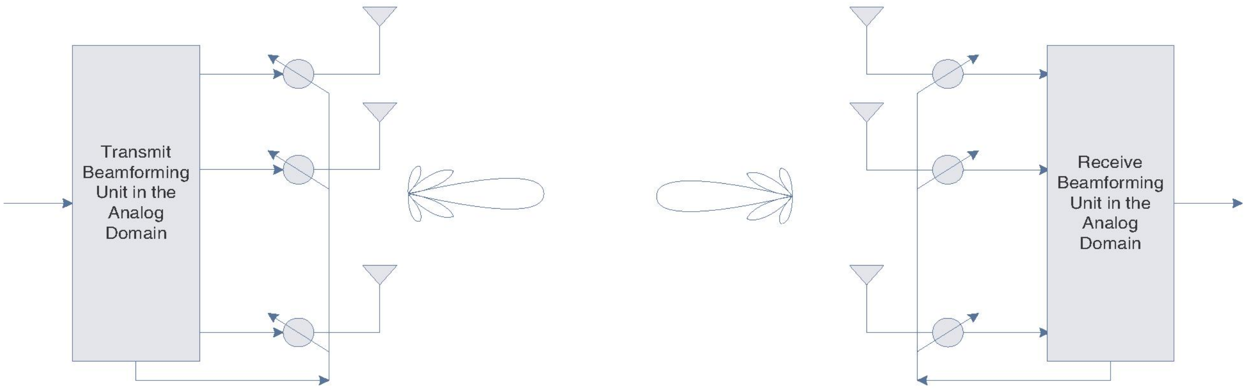

Fig. 1. Illustration of the antenna array beamforming.

non-line-of-sight (NLOS) propagation makes the link budget even poorer in many cases. Also, the 60GHz frequency band happens to be in the so-called oxygen absorption band, which means that transmitted energy is quickly absorbed by oxygen molecules in the atmosphere over long distances, making it unsuitable for long range radio communications.

Thus given the lossy and multi-path nature of the 60GHz radio channel as well as the immature CMOS technology, Gbps communications in the 60GHz band becomes extremely difficult. In general, to overcome the severe channel fading and atmospheric absorption, directional (or sectorized) antennas can be used, enabling highly focused radio links and improved link budget. However, directional antenna suffers from poor flexibility in that it can not be easily tuned toward different directions, where the potential transmitter/receiver is located.

Directional transmission based on antenna array beamforming thus emerges as an attractive solution, featuring high beamforming gain and electronically steerability. Due to the extremely short wavelength, it becomes possible and beneficial to integrate a large number of antenna elements on the whole package. With the availability of multiple antennas at both transmitter and receiver, the standard MIMO approach based on spatial multiplexing and space time codes is naturally one potential candidate. The problem, however, with the standard MIMO approach is the requirement for multiple RF chains, which becomes dramatically expensive considering the mm-wave paradigm. Fortunately, the major problem with the mm-wave communications is not the bandwidth efficiency issue, since a large bandwidth of up to 7 GHz is available to our use. Instead, improving link budget becomes the paramount concern to system designers. For this reason, simple 1-dimensional antenna array beamforming would be enough, which requires only 1 RF chain at either side of the transceiver, see Fig. 1.

One benefit of using antenna array beamforming is that the multi-path delay spread can be significantly reduced thanks to directional transmission. Transceiver baseband design can thus be simplified considerably, allowing simpler equalization and lower resolution ADCs to be employed. It is also possible to employ distributed power amplifiers across the antenna array so that the power amplification task can be shouldered by multiple power amplifier elements, each associated with a single antenna element.

C. Modulation Method

Modulation method for Gbps mm-wave communications is of critical importance as well. In particular, orthogonal frequency division multiplexing (OFDM), single carrier modulation with frequency domain equalization (SC-FDE), and minimum shift keying (MSK) are the most appealing candidates among others. In particular, MSK strikes a handsome tradeoff between implementation complexity and bandwidth efficiency, and would be a nice candidate for simple devices with fast time-to-market and low cost.

On the other hand, OFDM/SC-FDE target for higher bandwidth efficiency at the cost of larger implementation complexity, and thus would be suitable for higher end mm-wave devices. Conceptually, OFDM transmits multiple carriers in parallel with each occupying a narrow band, while SC-FDE transmits a single carrier modulated at a high symbol rate. Nevertheless, block-wise system diagram of the two systems are quite similar, as shown in Figure 2.

For OFDM, inverse FFT and FFT operations reside in transmitter and receiver respectively, while for SC-FDE, both inverse FFT and FFT operations are carried out at the receiver side. Linear MMSE equalization can be adopted for both schemes. Although the overall transceiver complexity are comparable, the respective transmitter/receiver complexity load is very imbalanced for SC-FDE. Thus, SC-FDE [2] in general would feature a low cost transmitter and a high cost receiver. This is highly undesirable for home network environment. It has also been shown in [3] that with channel state information available at the transmitter, the multi-carrier solution outperforms its single-carrier alternative, while enjoying even lower complexity.

Because the transmitted OFDM signal is the addition of a number of independently modulated subcarriers, it has a high peak to average ratio (PAPR), necessitating frequent power

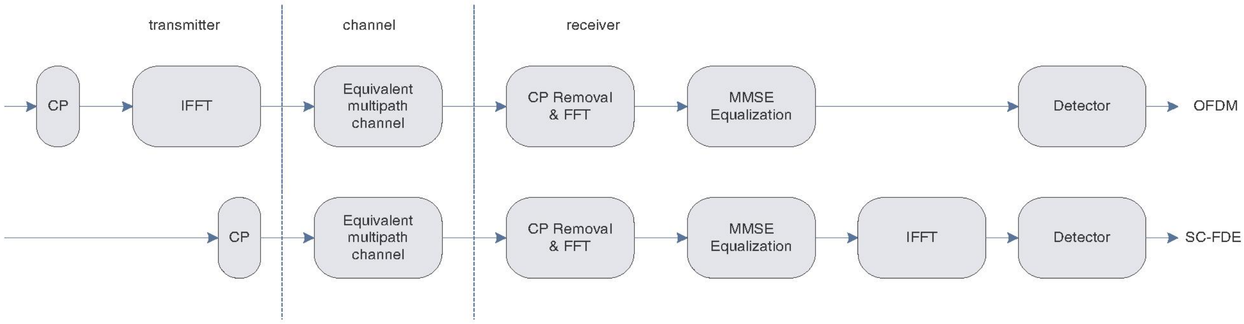

Fig. 2. System Diagrams of OFDM and SC-FDE.

amplifier back-off. Various PAPR reduction techniques can be used to alleviate the problem. Also, OFDM is more sensitive to carrier frequency offset, due to transmit and receive oscillator mismatch as well as Doppler effect.

Overall, both OFDM and SC-FDE are strong candidates for mm-wave communications targeting multiple Gbps throughput. Choice of the final modulation method involves an interesting tradeoff among various factors, including error rate performance, complexity, cost and others.

Coding and interleaving are essential to improve the system performance for both SC and OFDM schemes. In particular, OFDM can not live without coding, since uncoded OFDM system suffers from diversity loss due to channel diagonalization. Relying on trellis codes, it is demonstrated [4] that a single carrier system is slightly favorable when the code rate is high while the multi-carrier system is slightly favorable when the code rate is low. Notice that other than the conventional Galois field coding, the so-called complex field coding [5] (also known as linear precoding) can also be employed to improve the system robustness against channel fading without sacrificing channel bandwidth.

III. Challenges and Technologies in MAC Layer

MAC layer plays a critical role in moderating the access right to the shared wireless channel in 60GHz wireless. One fundament performance metric is efficiency, which is defined as the amount of time spent in transmitting data over total time including control message overhead, channel sensing, contention, channel switching duration, etc. In order to support multi-gigabit data-rate at the MAC-SAP, MAC efficiency should be targeted at 80% and beyond.

Peculiar to 60GHz wireless networks, the physical layer is typically equipped with an adaptive antenna array so that a directional beam is formed to maximize SINR (signal-to-interference and noise ratio). Directional transmission reduces potential collision zone by focusing the transmit power in a cone-like pattern. Control signaling need be exchanged in advance to setup such a directional link, before final payload communication takes place. However, since the angular information is not known *a priori* to the transceiver pair, the control signalings have to be communicated in an omni-directional fashion. For this reason, both omni-directional and directional transmissions/receptions need be supported by the 60GHz MAC. Absolute care is required in matching the range of the two transmission modes to avoid the exposed/hidden terminal problem otherwise.

An important feature at the MAC layer is to perform retransmissions. However, this option introduces additional delay, which may not be acceptable for low latency uncompressed video delivery. Furthermore, retransmissions need complex buffer management both at the source and at the sink. In the presence of limited retransmissions, the MAC can perform other error concealment techniques to overcome the effects of lost video signals.

A. Multiplexing and Channel Access Schemes

Possible techniques for multiplexing and channel access in 60GHz mmWave band are presented in this section.

1) Multiplexing: A wireless channel is *half-duplex*, that is, a node can either receive or transmit, but not both. This is because while a node is transmitting, a large amount of the signal energy leaks into the receiving circuitry. Duplexing may be done using frequency or time domain techniques. *Frequency division duplexing* (FDD) provides two distinct bands of frequencies for every user. *Time division duplexing* (TDD) uses time instead of frequency to provide both forward and reverse links. In TDD, multiple users share a single radio channel by taking turns in the time domain. Individual users are allowed to access the channel in their assigned *time slot*. In contrast to FDD, which requires two channels, TDD allows communication on a single channel. In FDD, besides 60GHz other potential candidates for the reverse channel are Bluetooth, RFID, UWB, WLAN, etc.

2) Medium Access Control: We can classify MAC protocols depending on the channel access methods as *contention-based* MAC protocols (Random, Distributed) or *contention-free* MAC protocols (Centralized, Scheduled). TDMA and FDMA are examples of contention-free MAC protocols. In a *contention-based* MAC protocol, all nodes contend for access to the shared wireless channel. A packet transmission is successful when only *one* node attempts to transmit the packet. When multiple nodes transmit simultaneously, a collision occurs and a contention resolution algorithm is invoked. Some of the popular *contention-based* MAC protocols are Pure Aloha, Slotted-Aloha (S-Aloha), and Carrier Sense Multiple Access (CSMA) [8]. In TDMA based protocol, such as IEEE 802.15.3, a coordinator periodically sends beacons that informs besides other things time-synchronization, contention free periods, contention periods, etc. In contrast to contention-based MAC protocols, TDMA based protocols are well suited for 60GHz isochronous applications, such as uncompressed video, which demand a strict QoS (quality of service) with predicted delay, low jitter and guaranteed bandwidth.

The 60GHz MAC should support both directional and omni-directional transmissions. The 60GHz MAC should schedule the omni- and directional-transmission in different TDMA slots since a device beamformed towards a specific angular direction cannot receive signals from the other directions. Moreover, such transmissions happening simultaneously within one TDMA slot would create interferences.

There are a number of techniques to improve the MAC-SAP efficiency such as a large packet size of the order of hundreds of kilo bytes, data aggregation, block-ack, etc. The header part of the MAC frame is crucial, because if header has some bit errors in it, usually the whole packet is useless. The MAC efficiency can also be improved by providing two CRCs (cyclic redundancy checksum): one for the MAC/PHY header (HCS) and other for the payload (FCS).

B. Device Discovery

In 60GHz wireless networks, device discovery becomes a challenging task because of the use of directional transmissions. When a new device joins the network, without any location information *a priori*, the transmitter needs to transmit at all directions (the receiver needs to receive at all directions as well). One way of achieving this using directional transmissions is to let the transmitter scan the entire spatial space. This can be done by possibly dividing the entire space into several sectors and let the transmitter focus on one sector at a time. The same principle applies to directional reception as well. Typically, if we have k sectors at one side, it may take as many as $k \times k$ time slots for one pair of devices to discover each other. As the number of sectors increases, the amount of time it takes for a pair of devices to discover each other also increases.

The hidden terminal problem which is common to all the wireless networks is aggravated in 60GHz wireless networks. Particularly, devices can be hidden to each other not only because of distance separation, but also because of directional difference. For example, devices can be hidden to each other when they are within the communication range but not transmitting or receiving in a certain direction. This problem is referred to as a directional hidden terminal problem or hidden beam problem [6].

Device discovery mechanism in 60GHz wireless networks are discussed herein briefly for two topologies: centralized topology and ad-hoc topology. For centralized topology where one device serves as a coordinator, and the coordinator is responsible for device discovery. One technique is to emulate omni-directional transmissions by switching transmission directions by the coordinator. When a new device joins in, it scans all directions and associates with the coordinator. For an ad-hoc topology where there is no coordinator, the overhead for each device to discover new devices is usually higher than the centralized topology. One design [7] to overcome this problem is to let the existing devices transmit beacons periodically at a beacon period. The new devices after listening for the beacon period can choose to associate with one of the devices or to transmit beacons itself using the beacons period. However, the efficiency of the device discovery is yet to be improved for both topologies.

IV. Challenges and Technologies in APP Layer

Using 60GHz technology, the high data rate achievable allows transmission of uncompressed audio and video over the wireless media. Content protection therefore is required by content providers. One challenge for content protection is the cipher speed for such high data throughput. Two types of ciphers considered are stream ciphers and block ciphers. Stream ciphers have higher speed and easier implementation, while block ciphers tend to have a stronger encryption strength but with slower speed. In order to meet the high speed encryption requirement, parallel cipher is considered, where several ciphers process the data in parallel. Latency and load balancing are two factors to be taken into consideration when design the parallel cipher.

Content protection protocols are mostly developed for wired cases. Protocols, such as High-bandwidth Digital Content Protection (HDCP) and Digital Transmission Content Protection (DTCP), are among the candidates which are considered to be extended to wireless networks. Potential issues are error propagation and control message exchange. Wireless channels are error prone, because of encryption, one bit error in the cipher text might cause many bits in error after decryption. The method of exchanging control information affects the efficiency. To improve the efficiency, control information can be integrated into frame headers.

Proximity control is another requirement for the content protection in 60GHz networks. Basically, audio and video transmissions should be limited within a certain range, so that content will not be broadcast to area where it is not intended to. One method commonly used is the RTT(Round Trip Time) test. Round trip time is measured from the time a probe message is sent to the time when a probe response is received. The proximity control requires the RTT time to be within some limit, otherwise the connection request will be rejected. Other proximity control schemes are authorization token and distance measurement, etc.

V. Conclusion

This paper presents various challenges and enabling technologies in realizing multi Gbps wireless networks in the mm-wave frequency band around 60GHz. Accurate CMOS RF modeling and circuit design is one of the most important challenges while research effort is working to answer this challenge. In the physical layer, poor link budget and NLOS propagation pose another important challenges, and can potentially be overcome by antenna array beamforming. Parallel baseband processing is generally favored in order to achieve multi Gbps throughput. Both OFDM and SC with FDE have their respective merit and drawback, making choice of the modulation method an interesting tradeoff.

In higher layers, hidden beam problem complicates the overall design and calls for careful MAC protocol development. Aggregation, block ACK are powerful tools in improving the MAC efficiency and assuring the targeted multi-Gbps throughput. Finally, content protection protocols in the multi-Gbps wireless paradigm need be carefully developed to support audio/video streaming over 60GHz wireless networks.

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