An Introduction to Millimeter-Wave Mobile Broadband Systems

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ABSTRACT

Almost all mobile communication systems today use spectrum in the range of 300 MHz–3 GHz. In this article, we reason why the wireless community should start looking at the 3–300 GHz spectrum for mobile broadband applications. We discuss propagation and device technology challenges associated with this band as well as its unique advantages for mobile communication. We introduce a millimeter-wave mobile broadband (MMB) system as a candidate next-generation mobile communication system. We demonstrate the feasibility for MMB to achieve gigabit-per-second data rates at a distance up to 1 km in an urban mobile environment. A few key concepts in MMB network architecture such as the MMB base station grid, MMB inter- BS backhaul link, and a hybrid MMB + 4G system are described. We also discuss beamforming techniques and the frame structure of the MMB air interface.

INTRODUCTION

Mobile communication has been one of the most successful technology innovations in modern history. The combination of technology breakthroughs and attractive value proposition has made mobile communication an indispensable part of life for 5 billion people. Due to the increasing popularity of smart phones and other mobile data devices such as netbooks and ebook readers, mobile data traffic is experiencing unprecedented growth. Some predictions indicate that mobile data will grow at 108 percent compound annual growth rate (CAGR) [1] with over a thousandfold increase over the next 10 years. In order to meet this exponential growth, improvements in air interface capacity and allocation of new spectrum are of paramount importance.

The current fourth-generation (4G) systems including LTE and Mobile WiMAX already use advanced technologies such as orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), multi-user diversity, link adaptation, turbo code, and hybrid automatic repeat request (HARQ) in order to achieve spectral efficiencies close to theoretical limits in terms of bits per second per Hertz per cell [2]. With limited room for further spectral efficiency improvement, another possibility to increase capacity per geographic area is to deploy many smaller cells such as femtocells and heterogeneous networks. However, because capacity can only scale linearly with the number of cells, small cells alone will not be able to meet the capacity required to accommodate orders of magnitude increases in mobile data traffic.

As the mobile data demand grows, the sub-3 GHz spectrum is becoming increasingly crowded. On the other hand, a vast amount of spectrum in the 3–300 GHz range remains underutilized. The 3–30 GHz spectrum is generally referred to as the super high frequency (SHF) band, while 30–300 GHz is referred to as the extremely high frequency (EHF) or millimeter-wave band. Since radio waves in the SHF and EHF bands share similar propagation characteristics, we refer to 3–300 GHz spectrum collectively as millimeter-wave bands with wavelengths ranging from 1 to 100 mm.

Millimeter-wave communication systems that can achieve multigigabit data rates at a distance of up to a few kilometers already exist for point-to-point communication. However, the component electronics used in these systems, including power amplifiers, low noise amplifiers, mixers, and antennas, are too big in size and consume too much power to be applicable in mobile communication. The availability of the 60 GHz band as unlicensed spectrum has spurred interest in gigabit-per-second short-range wireless communication. Several industrial standards have been developed, such as WirelessHD technology, ECMA-387, IEEE 802.15.3c, and IEEE 802.11ad. Integrated circuit (IC)-based transceivers are also available for some of these technologies. Much of the engineering efforts have been invested in developing more power-efficient 60 GHz RFICs [3]. Many of these technologies can be transferred to RFIC design for other millimeter-wave bands.

In this article, we explore the 3–300 GHz spectrum and describe a millimeter-wave mobile broadband (MMB) system that utilizes this vast spectrum for mobile communication. We describe the millimeter-wave spectrumand its propagation characteristics. We then discuss the network architecture, followed by the air interface design of the MMB system. After that, we conclude the article with a summary and brief discussion of future work.

The portion of the RF spectrum above 3 GHz has been largely unexploited for commercial wireless applications. More recently there has been some interest in exploring this spectrum for short-range and fixed wireless communications.

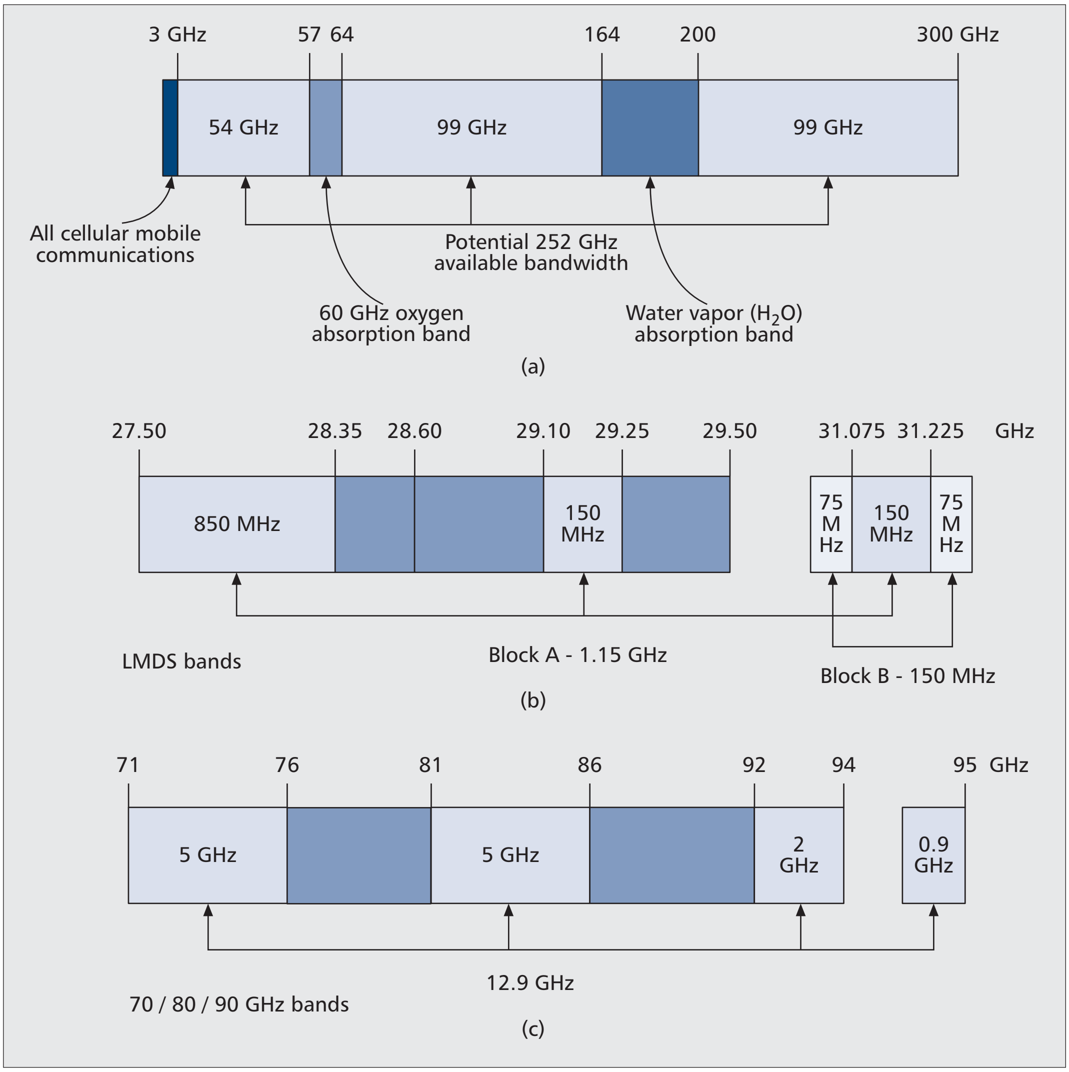

Figure 1. *Millimeter-wave spectrum.*

Millimeter Wave Spectrum

Unleashing the 3–300 GHz Spectrum

Almost all commercial radio communications including AM/FM radio, high-definition TV, cellular, satellite communication, GPS, and Wi-Fi have been contained in a narrow band of the RF spectrum in 300 MHz–3 GHz. This band is generally referred to as the *sweet spot* due to its favorable propagation characteristics for commercial wireless applications. The portion of the RF spectrum above 3 GHz, however, has been largely unexploited for commercial wireless applications. More recently there has been some interest in exploring this spectrum for short-range and fixed wireless communications. For example, unlicensed use of ultra-wideband (UWB) in the range of 3.1–10.6 GHz frequencies has been proposed to enable high data rate connectivity in personal area networks. The use of the 57–64 GHz oxygen absorption band is also being promoted to provide multigigabit data rates for short-range connectivity and wireless local area networks. Additionally, local multipoint distribution service (LMDS) operating on frequencies from 28 to 30 GHz was conceived as a broadband, fixed wireless, point-to-multipoint technology for utilization in the last mile.

Within the 3–300 GHz spectrum, up to 252 GHz can potentially be suitable for mobile broadband as depicted in Fig. 1a. Millimeter waves are absorbed by oxygen and water vapor in the atmosphere. The frequencies in the 57–64 GHz oxygen absorption band can experience attenuation of about 15 dB/km as the oxygen molecule (O_2) absorbs electromegnetic energy at around 60 GHz. The absorption rate by water vapor (H_2O) depends on the amount of water vapor and can be up to tens of dBs in the range of 164–200 GHz [4]. We exclude these bands for mobile broadband applications as the transmission range in these bands will be limited. With a reasonable assumption that 40 percent of the remaining spectrum can be made available over time, millimeter-wave mobile broadband (MMB) opens the door for a possible 100 GHz new spectrum for mobile communication — more than 200 times the spectrum currently allocated for this purpose below 3 GHz.

LMDS and 70/80/90 GHz Bands

LMDS was standardized by the IEEE 802 LAN/MAN Standards Committee through the efforts of the IEEE 802.16.1 Task Group (“Air Interface for Fixed Broadband Wireless Access

Systems" for 10–66 GHz). LMDS uses a cellular infrastructure, with multiple base stations supporting point-to-multipoint communication to small customer transceivers. The Federal Communications Commission (FCC) auctioned two LMDS licenses per market (basic trading areas). The A license includes a total of 1.15 GHz bandwidth, and consists of the 27.5–28.35 GHz, 29.1–29.25 GHz, and 31.075–31.225 GHz bands. The B license is 150 MHz wide, covering the 31.0–31.075 GHz and 31.225–31.3 GHz bands as depicted in Fig. 1b.

On October 16, 2003 the FCC announced that the 71–76 GHz, 81–86 GHz, and 92–95 GHz frequency bands collectively referred as E-band had become available to ultra-high-speed data communication including point-to-point wireless local area networks, mobile backhaul, and broadband Internet access. A total of 12.9 GHz bandwidth is available in the E-band as shown in Fig. 1c, with a narrow 100 MHz exclusion band at 94.0–94.1 GHz. Highly directional "pencilbeam" signal characteristics in E-band permit systems in these bands to be engineered in close proximity to one another without causing interference. Therefore, the FCC and regulators in other countries have introduced "light licensing" schemes for managing this band. These innovative licenses retain the benefits of full interference protection and can be applied for in minutes over the Internet at costs of a few tens of dollars per year.

We note that regulations would need to be changed with provisioning to support mobility and higher transmit powers to enable mobile broadband communications in LMDS, 70/80/90 GHz, and possibly other millimeter-wave bands.

		Attenuation (dB)		
Material	Thickness (cm)	< 3 GHz [6, 8]	40 GHz [7]	60 GHz [6]
Drywall	2.5	5.4	–	6.0
Office whiteboard	1.9	0.5	–	9.6
Clear glass	0.3/0.4	6.4	2.5	3.6
Mesh glass	0.3	7.7	–	10.2
Chipwood	1.6	–	.6	–
Wood	0.7	5.4	3.5	–
Plasterboard	1.5	–	2.9	–
Mortar	10	–	160	–
Brick wall	10	–	t178	–
Concrete	10	17.7	175	–

Table 1. *Attenuations for different materials.*

Millimeter-Wave Propagation

Free-Space Propagation

Transmission loss of millimeter wave is accounted for principally by free space loss. A general misconception among wireless engineers is that free-space propagation loss depends on frequency, so higher frequencies propagate less well than lower frequencies. The reason for this misconception is the underlying assumption often used in radio engineering textbooks that the path loss is calculated at a specific frequency between two isotropic antennas or $\lambda/2$ dipoles, whose effective aperture area increases with the wavelength (decreases with carrier frequency). An antenna with a larger aperture has larger gain than a smaller one as it captures more energy from a passing radio wave. However, with shorter wavelengths more antennas can be packed into the same area. For the same antenna aperture areas, shorter wavelengths (higher frequencies) should not have any inherent disadvantage compared to longer wavelengths (lower frequencies) in terms of free space loss [5]. In addition, large numbers of antennas enable transmitter and receiver beamforming with high gains. For example, a beam at 80 GHz will have about 30 dB more gain (narrower beam) than a beam at 2.4 GHz if the antenna areas are kept constant.

Penetration and Other Losses

For 3–300 GHz frequencies, atmosphere gaseous losses and precipitation attenuation are typically less than a few dB per kilometer [4], excluding the oxygen and water absorption bands. The loss due to reflection and diffraction depends greatly on the material and the surface. Although reflection and diffraction reduce the range of millimeter-wave, it also facilitates non-line-of-sight (NLOS) communication.

While signals at lower frequencies can penetrate more easily through buildings, millimeter-wave signals do not penetrate most solid materials very well. In Table 1, we provide attenuation values for common materials [6, 7]. High levels of attenuation for certain building materials (e.g., brick and concrete) may keep millimeter waves transmitted from outdoor base stations confined to streets and other outdoor structures, although some signals might reach inside the buildings through glass windows and wood doors. The indoor coverage in this case can be provided by other means such as indoor millimeter-wave femtocell or Wi-Fi solutions. It should be noted that next-generation Wi-Fi technology using 60 GHz millimeter waves is already being developed in IEEE 802.11ad [9].

Foliage losses for millimeter waves are significant and can be a limiting impairment for propagation in some cases. An empirical formula has been developed in [6] to calculate the propagation through foliage. In Fig. 2a, we plot penetration losses for foliage depth of 5, 10, 20, and 40 m. We note, for example, that at 80 GHz frequency and 10 m foliage penetration, the loss can be about 23.5 dB, which is about 15 dB higher than the loss at 3 GHz frequency.

Millimeter-wave transmissions can experience significant attenuations in the presence of heavy rain. Raindrops are roughly the same size as the radio wavelengths (millimeters) and therefore cause scattering of the radio signal. The attenuation (dB per kilometer) can be calculated from rain rates (millimeters per hour) [10], and the curves are plotted in Fig. 2b. For example, light

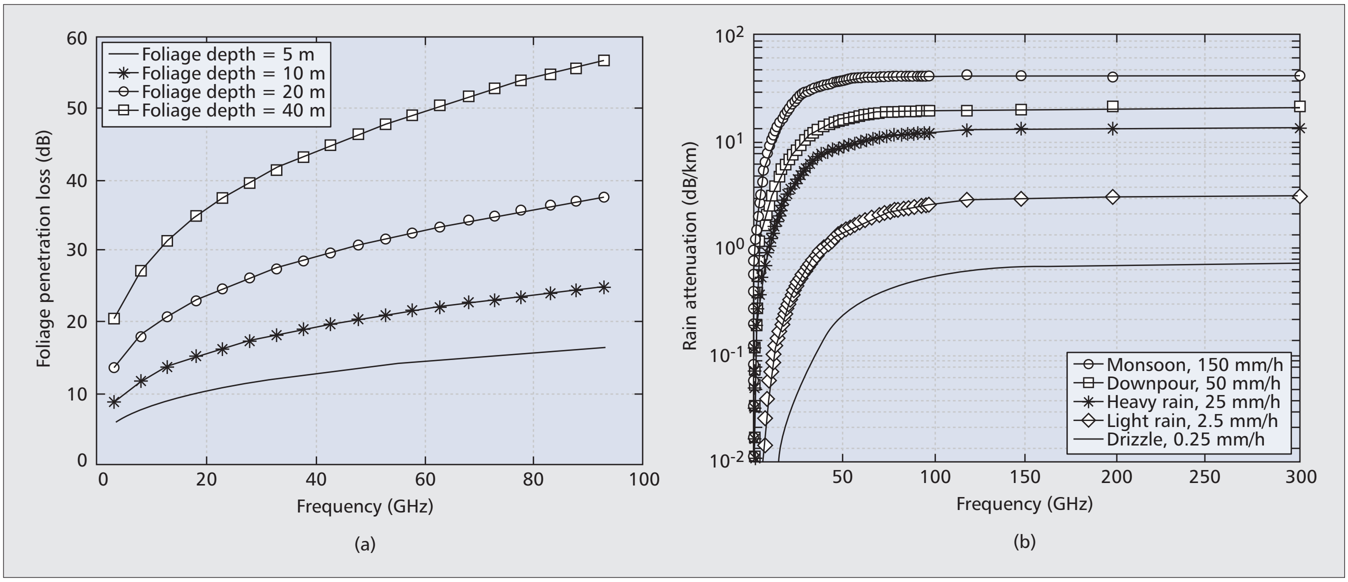

Figure 2. *Millimeter-wave propagation characteristics: a) foliage penetration loss; b) rain attenuation.*

rain at a rate of 2.5 mm/h yields just over 1 dB/km attenuation, while severe rain such as a monsoon at a rate of 150 mm/h can jeopardize communications with up to tens of dB loss per kilometer at millimeter-wave frequencies. Fortunately, the most intense rain tends to fall in selected countries of the world, and happen in short bursts and small clusters. A mechanism such as supporting emergency communications over cellular bands when millimeter-wave communications are disrupted by heavy rains should be considered as part of the MMB system design.

Doppler and Multipath

The Doppler of a wireless channel depends on the carrier frequency and mobility. Assuming a rich scattering environment and omnidirectional antennas, the maximum Doppler shift for carrier frequency of 3–60 GHz with mobility of 3–350 km/h ranges from 10 Hz to 20 kHz. The Doppler shift values of incoming waves on different angles at the receiver are different, resulting in a phenomenon called Doppler spread. In the case of MMB, the narrow beams at the transmitter and receiver will significantly reduce angular spread of the incoming waves, which in turn reduces the Doppler spread. In addition, as the incoming waves are concentrated in a certain direction, there will be a non-zero bias in the Doppler spectrum, which will be largely compensated by the automatic frequency control (AFC) loop in the receiver. Therefore, the time-domain variation of an MMB channel is likely to be much less than that observed by omnidirectional antennas in a rich scattering environment.

With narrow transmitter and receiver beams, the multipath components of millimeter waves are limited. Studies show that the root mean square (RMS) of the power delay profile (PDP) of a millimeter-wave channel in an urban environment is 1–10 ns, and the coherent bandwidth of the channel is around 10–100 MHz [11]. However, it is noted that the transmitter and receiver antenna gains used in these studies are higher than those used in MMB. Therefore, it is possible that in an MMB system a longer path can be observed and the coherence bandwidth is smaller than those reported in these studies.

MMB Network Architecture

A Standalone MMB Network

An MMB network consists of multiple MMB base stations that cover a geographic area. In order to ensure good coverage, MMB base stations need to be deployed with higher density than macrocellular base stations. In general, roughly the same site-to-site distance as microcell or picocell deployment in an urban environment is recommended. An example MMB network is shown in Fig. 3.

The transmission and/or reception in an MMB system are based on narrow beams, which suppress the interference from neighboring MMB base stations and extend the range of an MMB link. This allows significant overlap of coverage among neighboring base stations. Unlike cellular systems that partition the geographic area into cells with each cell served by one or a few base stations, the MMB base stations form a grid with a large number of nodes to which an MMB mobile station can attach. For example, with a site-to-site distance of 500 m and a range of 1 km for an MMB link, an MMB mobile station can access up to 14 MMB base stations on the grid, as shown in Fig. 3a. The MMB base station grid eliminates the problem of poor link quality at the cell edge that is inherent in cellular system and enables high-quality equal grade of service (EGOS) regardless of the location of a mobile.

With the high density of MMB base stations, the cost to connect every MMB base station via a wired network can be significant. One solution to mitigate the cost (and expedite the deployment) is to allow some MMB base stations to connect to the backhaul via other MMB base stations. Due to large beamforming gains, the MMB inter-BS backhaul link can be deployed in the same frequency as the MMB access link —

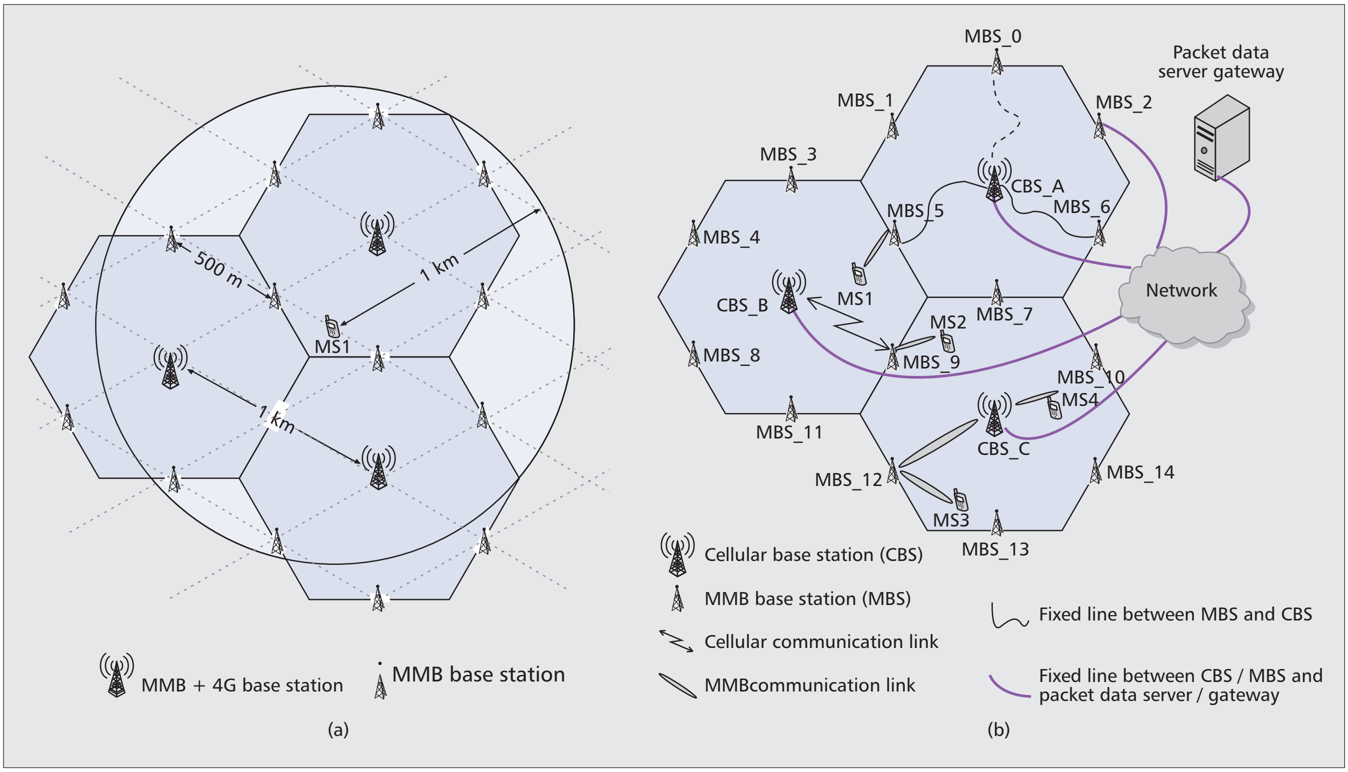

Figure 3. *MMB network: a) architecture; b) hybrid MMG + 4G system.*

the downlink to and uplink from an MMB mobile station — without causing much interference. This greatly increases the deployment flexibility of MMB and allows MMB to achieve higher-density deployment than femtocells or heterogeneous networks deployed in sub-3 GHz spectrum.

Another challenge with millimeter-wave is the low efficiency of RF devices such as power amplifiers and multi-antenna arrays with current technology. A solution to avoid multi-antenna arrays at the MMB base station is to use fixed beams or sectors with horn antennas. Horn antennas can provide similar gains and beam widths as sector antennas in current cellular systems in a cost-effective manner [12]. The mobile station receiver still needs to use a multi-antenna array to form a beamforming pattern toward the base station. As the mobile station moves around, beamforming weights can be adjusted so that the beam is always pointing toward the base station.

Hybrid MMB + 4G System

In the early deployment of MMB, there may be coverage holes in areas where the MMB base station density is low. However, it is expected that 4G systems will have good coverage and reliability when MMB systems start to deploy. A hybrid MMB + 4G system can improve coverage and ensure seamless user experience in mobile applications. In a hybrid MMB + 4G system, system information, control channel, and feedback are transmitted in the 4G system, making the entire millimeter-wave spectrum available for data communication. One example of a hybrid MMB + 4G system is shown in Fig. 3b. Compared with millimeter waves, the radio waves at < 3 GHz frequencies can better penetrate obstacles and are less sensitive to non-line-of-sight (NLOS) communication link or other impairments such as absorption by foliage, rain, and other particles in the air. Therefore, it is advantageous to transmit important control channels and signals via cellular radio frequencies, while utilizing the millimeter waves for high data rate communication.

MMB Air Interface Design

Beamforming

Beamforming is a signal processing technique used for directional signal transmission or reception. Spatial selectivity/directionality is achieved by using adaptive transmit/receive beam patterns. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter antenna to create a pattern of constructive and destructive interference in the wavefront. When receiving, signals from different receiver antennas are combined in such a way that the expected pattern of radiation is preferentially observed.

Beamforming is a key enabling technology of MMB. For MMB transceivers, the small size ($\lambda/2$ dipoles) and separation (also around $\lambda/2$) of millimeter-wave antennas allow a large number of antennas and thus achieve high beamforming gain in a relative small area (e.g., tens of antennas per square centimeter area at 80 GHz carrier frequency). Additionally, with a large number of antennas and high-gain (and thus narrow) beams, antenna technologies such as spatial-division multiple access (SDMA) can be implemented readily.

Beamforming can be achieved in digital base-

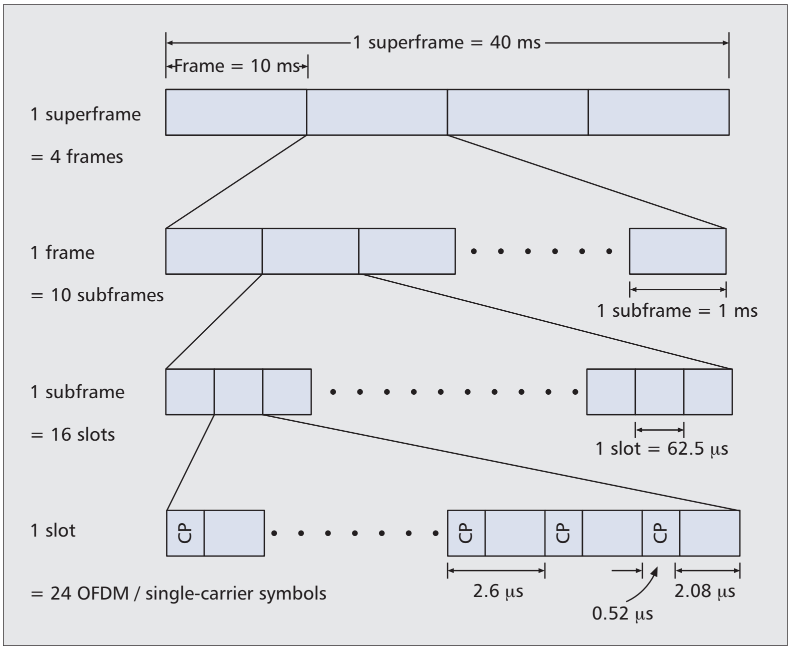

Figure 4. *MMB frame structure (1/4 CP).*

band, analog baseband, or RF front-end. With digital beamforming and multiple RF chains, it is possible to transmit multiple streams of data simultaneously, thus enabling SDMA or MIMO operation. However, the cost of implementing one RF chain per antenna can be prohibitive, especially given the large number of antennas in MMB. With analog baseband beamforming or RF beamforming, one or a few RF chains can be used. In that case, the number of data streams that can be transmitted is limited by the number of RF chains. These approaches require fewer RF components and are typically chosen for low-cost/low-power solutions.

Transmit beamforming is generally more challenging, requiring either antenna weights feedback from the receiver or antenna calibrations. Moreover, due to low efficiency of millimeter-wave power amplifiers with the current technology, battery power consumption is another issue for mobile station transmitter beamforming. To reduce the cost and complexity of mobile stations, a phased approach where initial deployments are hybrid MMB + 4G systems with downlink-only transmission in the millimeter-wave band can be considered. This removes the requirement for mobile stations to transmit in the millimeter-wave band.

Frame Structure

OFDM and single-carrier FDM were chosen to be the multiplexing schemes of 4G systems due to a variety of reasons (e.g., flexibility in support multiple bandwidths, simpler equalizer and MIMO receiver, and ability to support efficient multiple access, etc.). In MMB, we also use OFDM and single-carrier waveform for largely the same reasons.

One configuration of MMB frame structure is shown in Fig. 4. The basic transmission time interval (TTI) of MMB is a slot, whose duration is 62.5 us. In order to facilitate hybrid MMB + 4G operation, the durations of subframe, frame, and superframe are chosen to be 1 ms, 10 ms, and 40 ms, the same as those of LTE systems.

The OFDM/single-carrier numerology is carefully chosen according to a number of engineering considerations. For example, the sampling rate is chosen to be a multiple of 30.72 MHz, a popular frequency at which clocks with reasonable accuracy are readily available at low cost. The cyclic prefix (CP) is chosen to be 520 ns, which gives sufficient margin in accommodating the longest path, different deployment scenarios, and the potential increase of delay spread in the case of small antenna arrays (e.g., smart phones with small form factors) or wider beams (e.g., control channel transmissions). The subcarrier spacing is chosen to be 480 kHz, small enough to stay within the coherent bandwidth of most multipath channels expected in MMB. The corresponding OFDM symbol length (without CP) is 2.08 μs, resulting in 20 percent CP overhead. The subcarrier spacing is also wide enough to keep the size of fast/inverse fast Fourtier transform (FFT/IFFT) small (2048 points for 1 GHz system bandwidth) and accommodate inaccuracies of low-cost clocks. For example, with a carrier frequency of 28 GHz and a clock with 20 ppm accuracy, the clock drift is at most 560 kHz, less than 2 times the subcarrier spacing. This enables simple design of synchronization and system acquisition.

Additionally, MMB also supports transmission with single-carrier waveform. Single-carrier waveform has lower peak-to-average-power ratio (PAPR) than OFDM. As the solid-state devices today only have a limited amount of output power rating (< 1 W) in 60–100 GHz frequencies, it is beneficial to use single-carrier waveform to maximize the output power so that MMB can achieve the longest range possible. A lower PAPR also allows the receiver to use a low-resolution analog-to-digital converter (ADC). For single-carrier transmissions with binary phase shift keying (BPSK) or quaternary PSK (QPSK), an ADC with 2–4 bits would suffice, which greatly reduces the power consumption of the MMB receiver.

Link Budget

The key factors that determine the downlink link budget of an MMB system are the base station transmission power, transmitter and receiver beamforming gains, and path loss.

Table 2 shows the link budget for four different MMB systems. A 20 dB margin is assumed to account for cable loss and losses due to penetration, reflection, or diffraction. A noise figure of 10 dB and an implementation loss of 5 dB are assumed at the receiver. As shown in Table 2, with 35 dBm transmission power, 1 GHz system bandwidth, 28 GHz carrier frequency, and realistic assumptions of transmitter and receiver antenna gains (case 1), more than 2 Gb/s can be achieved at 1 km distance.

Conclusion

Millimeter-wave spectrum with frequencies in the range of 3–300 GHz can potentially provide the bandwidth required for mobile broadband applications for the next few decades and beyond.

In this article, we have analyzed the suitability of different millimeter-wave frequencies for mobile communication. We have discussed the propagation characteristics of millimeter waves, including the propagation and penetration losses, Doppler, and multipath. Due to the narrow beam width of MMB transmissions, the interference among MMB base stations is a lot smaller than traditional cellular systems, and the coverage of neighboring base stations significantly overlap. As a result, the MMB base stations form a grid that can provide communication with good link quality regardless of the mobile station's location within the coverage of the grid. The inter-BS backhaul link can be used to mitigate the cost of backhauling (and to expedite deployment). It is also possible to operate a hybrid MMB + 4G system such that existing 4G systems can be leveraged for reliable system information broadcast, packet data control, and feedback of MMB systems.

In order to operate in an urban mobile environment while keeping a low overhead, we chose the MMB subcarrier spacing to be 480 kHz and the CP to be 520 ns. We also designed the frame structure to facilitate hybrid MMB + 4G operation. In the link budget analysis, we show that a 2 Gb/s data rate is achievable at 1 km distance with millimeter waves in an urban mobile environment.

MMB link budget analysis	Case 1	Case 2	Case 3	Case 4
TX power (dBm)	35.00	35.00	25.00	25.00
TX antenna gain (dBi)	30.00	30.00	30.00	30.00
Carrier frequency (GHz)	28.00	72.00	28.00	72.00
Distance (km)	1.00	1.00	0.50	0.50
Propagation loss (dB)	121.34	129.55	115.32	123.53
Other losses	20.00	20.00	20.00	20.00
RX antenna gain (dBi)	15.00	15.00	15.00	15.00
Received power (dBm)	–61.34	–69.55	–65.32	–73.53
Bandwidth (GHz)	1.00	1.00	1.00	1.00
Thermal PSD (dBm/Hz)	–174.00	–174.00	–174.00	–174.00
Noise figure (dB)	10.00	10.00	10.00	10.00
Thermal noise (dBm)	–74.00	–74.00	–74.00	–74.00
SNR (dB)	12.66	4.45	8.68	0.47
Implementation loss (dB)	5.00	5.00	5.00	5.00
Data rate (Gb/s)	2.77	0.91	1.74	0.4

Table 2. *MMB link budget.*

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