
Millimeter-Wave Wireless Communication

Millimeter-wave frequencies often refer to the frequency range from 30GHz to 300GHz, the wavelength of which is between 10mm to 1mm. There are several motivations for wanting to use mm-wave frequencies in radio links:

- The radio spectrum at mm-wave frequencies is still rather undeveloped, and more bandwidth is available at these frequencies.
- Because of higher attenuation in free space and through walls at mm frequencies, the same frequency can be reused at shorter distances.
- The inherent security and privacy is better at mm-wave frequencies because of the limited range and the relatively narrow beam widths that can be achieved.
- The spatial resolution is better at mm-wave frequencies since the small wavelength allows modest size antennas to have a small beam width.
- The physical size of antennas at mm-wave frequencies becomes so small that it becomes practical to build complex antenna arrays and/or further integrate them on chip or PCB.

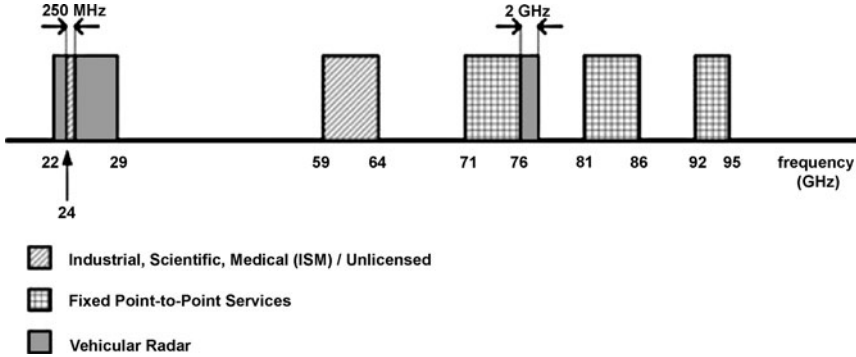


Figure 2.1: Millimeter-wave band allocation in the United States [11]

Figure 2.1 shows the mm-wave band allocation in the United States [11]. There is 5GHz bandwidth available at the 60GHz band (59–64GHz) for Industrial, Scientific and Medical (ISM) unlicensed applications. The 24GHz band (22–29GHz) band and 77GHz band (76–77GHz) are currently assigned to automotive radar. Fixed point-to-point communication links can use 71–76GHz, 81–86GHz and 92–96GHz that need a license in the USA from The Federal Communications Commission (FCC). The mm-wave frequency bands offer many new products and services, for example:

- The large bandwidth at 60GHz can provide unlicensed short-range high-speed links for WPAN (802.15.3c) and wireless high definition video streaming (Wireless HD). Data rates can be several Gbps.
- The 77GHz band is suitable for automotive long-range (100m) autonomous cruise-control (ACC) radar. The high carrier frequency allows modest-size antennas to have a small beam width and therefore a better angular resolution.
- The 24GHz band can be used in automotive short-range radar, since the large bandwidth at 24GHz offers sufficient small distance resolution (5cm).
- The large bandwidth at 71–76GHz, 81–86GHz and 92–96GHz can provide licensed high-speed links with data throughput up to 10Gbps.

- The natural thermal emission of objects in the 35GHz and 94GHz bands allows passive imaging to construct an image.

This chapter [12] is organized as follows. The unique mm-wave applications are discussed in Sect. 2.1. Section 2.2 presents system considerations of mm-wave receiver and transmitter front-ends. The technology choices to implement mm-wave systems are discussed in Sect. 2.3.

2.1 Millimeter-Wave Communication

2.1.1 Multi-Gbps Data Communication

In principle, a high data rate can be achieved by a combination of signal bandwidth and dynamic range. The limit for the data rate over a single-input and single-output (SISO) link is set by the capacity (C) of the link and is a function of the bandwidth (BW) and the signal-to-noise ratio (SNR) [32]:

$$C = \text{BW} \times \log_2(1 + \text{SNR}) \quad (2.1)$$

Therefore, a high data rate can be achieved with a low bandwidth if the SNR is high. However, a high SNR requires either a short distance between transmitter and receiver, or a high transmit power, or high gain antennas. This is described in the Friis Transmission equation:

$$P_{\text{sig}} = P_t \times G_r \times G_t \times \left(\frac{\lambda}{4\pi \times d} \right)^\alpha \quad (2.2)$$

In this equation, P_{sig} is the received signal power, P_t is the transmitted signal power, G_r is the gain of the receiver antenna, G_t is the gain of the transmitter antenna, λ is the wavelength, and d is the distance between the transmit and receive antennas. The original Friis transmission equation is valid for free space environments with a value of 2 for the parameter α . It is also used to approximate the average received power in multi-path environments inside buildings, in which case the parameter α varies from 1.8 to 5.2 and is higher for higher frequencies because of reduced transmission through typical walls [33].

On the other hand, the input-referred integrated noise power of the receiver can be expressed as [34]:

$$N_{\text{in}} = k \times T \times \text{NF} \times \text{BW} \quad (2.3)$$

In this equation, k is the Boltzmann constant and is equal to $1.38 \times 10^{-23} \text{ J/K}$, T is the absolute temperature. NF is the noise factor of the receiver ($\text{NF} \geq 1$).

By combining Eqs. 2.1, 2.2 and 2.3, the achievable data rate of a system can be expressed as function of bandwidth and frequency:

$$C = \text{BW} \times \log_2 \left(1 + \frac{P_t \times G_r \times G_t \left(\frac{\lambda}{4\pi \times d} \right)^\alpha}{k \times T \times \text{BW} \times \text{NF}} \right) \quad (2.4)$$

The impact of frequency and bandwidth on the achievable data rate is shown in Fig. 2.2 for a system with $d = 10\text{m}$, $P_t = 1\text{W}$. We assume half-wavelength dipole antennas at in free space ($\alpha = 2$) under line-of-sight situations, and the antenna size decreases at higher frequencies. This figure shows the achievable data rate as a function of frequency and bandwidth. The figure shows that data rates in excess of 10Gbps can be achieved for high bandwidths (1GHz) at low frequencies (1GHz).

The shape of the graph is caused by the different influences of bandwidth and SNR (and therefore indirectly frequency) on the channel capacity. Increasing bandwidth seem like an obvious way to improve the channel capacity, but it also increases the noise in the channel and therefore reduces the signal-to-noise ratio at a fixed signal level. Therefore, increasing bandwidth makes sense only if the SNR is sufficiently high. Since in in-house environments α is a function of frequency, the optimum at low frequencies will be even more pronounced than shown in Fig. 2.2. This, together with the higher transparency of walls at lower frequencies and the simpler and cheaper electronics, explains the popularity of relatively low frequencies for radio communication.

However, this inherently leads to a conflict: if all high data rate applications prefer to use a lot of bandwidth at low frequencies, then the radio spectrum at low frequencies will quickly fill up, which it indeed does. This results in a drive towards higher frequencies, since there will be more bandwidth available than at lower frequencies. In addition, the decrease

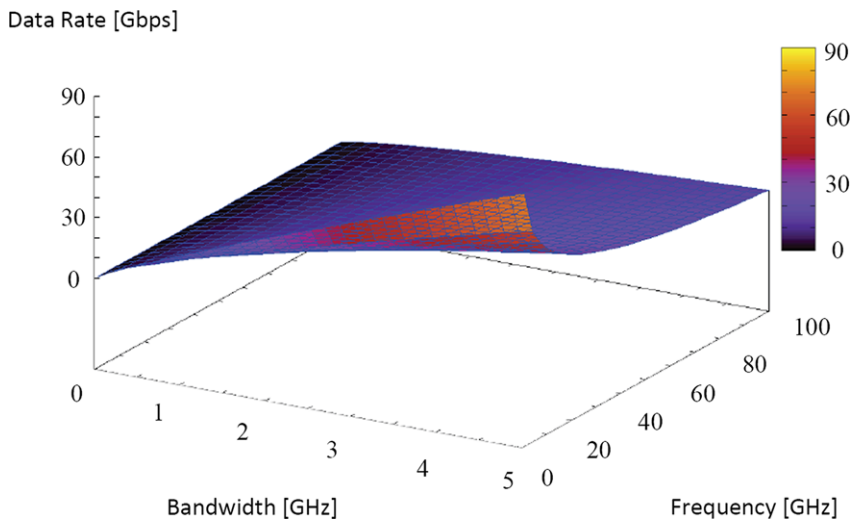


Figure 2.2: Achievable data rate versus frequency and bandwidth with half wavelength dipole antennas

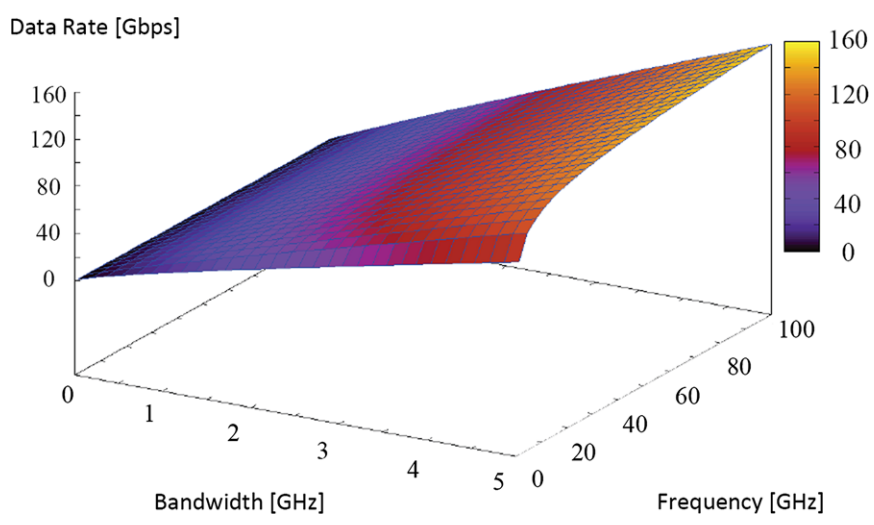


Figure 2.3: Achievable data rate versus frequency and bandwidth with antenna size fixed to a 900MHz dipole antenna

in data rate when increasing the frequencies as shown in Fig. 2.2 is somewhat deceptive, in that it is caused by the decrease in antenna size at higher frequencies. If we keep the physical antenna size the same as a 900MHz dipole antenna (by setting λ to a constant λ_0 in Eq. 2.4), the achievable data rate of a system can be expressed as:

$$C = BW \times \log_2 \left(1 + \frac{P_t \times G_r \times G_t \left(\frac{\lambda_0}{4\pi \times d} \right)^\alpha}{k \times T \times BW \times NF} \right) \quad (2.5)$$

According to Eq. 2.5, there is no decrease in data rate with higher frequencies, and the achievable data rate still increases significantly with the bandwidth, as shown in Fig. 2.3.

From these two results, high data rate radio links with high bandwidths at high frequencies (60GHz) make sense when electrically large antennas ($\gg \lambda/2$) are used, which provide antenna gain and directivity.

2.1.2 Automotive Radar

The basic principle of radar is that an RF signal is transmitted towards the target of interest, which is reflected from the target and then received by the radar antenna. Information regarding the distance, relative speed and angular position of the target is detected using the reflected signal. For instance, in either a pulse radar or a frequency modulated continuous-wave (FM-CW) radar, the distance of the target can be detected directly or indirectly utilizing the time for the signal to travel to the target and return. Speed can be detected by utilizing the change of distance with respect to time, or utilizing the frequency shift (Doppler Effect) of reflected signals. The angular position of the target can be determined by exploiting the directive gain of the antenna in different directions. When a certain antenna aperture is used, the angular resolution improves with higher RF carrier frequency. Furthermore, in most cases the receiver does not detect the reflected signal while the signal is being transmitted. The minimal detection range in a pulse radar is therefore determined by the pulse length. In order to detect closer targets, a shorter pulse will be used, which requires a larger signal bandwidth. An FM-CW radar also needs larger signal bandwidth to detect closer targets.

Automotive radars, which have been available in high end cars, will be key components of future smart cars. The reason is that car safety is a serious issue in our lives: auto collisions are the leading cause of injury-related deaths, an estimated total of 1.2 million in 2004, or 25% of the total from all causes [35]. Pre-crash systems with automotive radars can detect an imminent crash and warn the driver and even help the vehicle itself to avoid a collision. As compared to visual and infrared (IR) sensors, the advantage of mm-wave radar is that it can be used not only in day and night conditions, but also in fog and other poor visibility conditions.

The 77GHz band (76–77GHz) can be applied to long-range (100m) autonomous cruise-control (ACC) radar, since the high carrier frequency results in a sufficient angular resolution. ACC radar helps maintain a safe distance to vehicles in front by automatically controlling vehicle speeds [36].

Short-range radars can use e.g. the 24GHz band (22–29GHz), since the large bandwidth offers sufficient small distance resolution (5cm). Short-range car radar has applications such as object detection, pedestrian detection and protection, parking aid, side-impact pre-crash detection and blind spot detection [11].

2.1.3 Millimeter-Wave Imaging

Millimeter-wave frequencies allow a spatial resolution of a few millimeters, which can be used for active and passive imaging [37]. Passive imaging detects natural thermal emissions of objects in the 35GHz and 94GHz bands, and forms the image of objects similar to an optical system. In an active imaging system, mm-wave signals are transmitted in order to “illuminate” objects.

Millimeter-wave imaging can operate not only in day and night conditions, but also in fog and other poor visibility conditions that normally blind visual and infrared (IR) cameras. It can help airport landing, airport operation, harbor surveillance and highway traffic monitoring [37].

Millimeter-wave imaging also has security applications such as concealed-weapon detection [37]. Since the mm-wave signatures of metallic objects are very different from body background, mm-wave imaging offers easy detection and few false alarms.

In addition, mm-wave imaging can be used in medical applications such as tumor detection, temperature measurement, blood flow and water/oxygen content measurement [11]. It has the advantage of being harmless to humans: passive imaging only use the natural thermal emission, and active imaging uses radiations with milli-eV energies. In contrast, X-ray based imaging systems require radiations with k-eV energies, and can only be used with limited dosage.

2.2 System Requirements

Although they are in many aspects similar to transceiver architectures at lower frequencies, transceiver architectures at mm-wave frequencies have to meet several different requirements.

As discussed in the previous section, one of the main motivations for implementing radio links at mm-wave frequencies is the availability of empty bands. These bands allow the use of wide bandwidth transmissions to achieve high data rates, as long as a sufficient signal-to-noise ratio can be achieved.

One way to relax the requirements on signal-to-noise ratio is the use of less bandwidth-efficient modulation schemes. Since the performance of RF circuits at mm-wave frequencies is limited, a (relatively) constant envelope modulation scheme such as FSK or QPSK modulation will be attractive. QPSK modulation is used in this work, since it can be extended to other varying-envelop modulation schemes (e.g. high-order PSK with or without OFDM).

A time domain multiple-access (TDMA) scheme fits best with simple modulation schemes. It reduces interference from adjacent and alternate channels that will occur in frequency division multiple access (FDMA) schemes, and easily allows flexible and on-demand allocation of total system capacity across multiple sources.

Because of the high free-space path loss at mm-wave frequencies, phased array technique is an attractive solution to compensate for the path loss and alleviate the requirements of RF transceiver front-ends. This will impact both architectural and circuit level requirements for mm-wave frequency transceivers. Separate receiver/transmitter paths are required for

each of the multiple antennas. Special attention has to be paid to phase consistency between the different receiver/transmitter paths. Therefore, a common VCO/synthesizer with a classical up-conversion transmitter and down-conversion receiver will be both cost-effective and robust, especially for single-chip integration of a phased array transceiver. However, it may be difficult to integrate a large number of receiver/transmitter paths on a single chip, due to the limitation of e.g. chip area, cross-talk, parasitic coupling and power consumption. In that case, it is preferred to have an individually modulated VCO/synthesizer in each chip, and minimize the distribution of high frequency RF or LO signals between the multiple chips.

A mm-wave receiver will usually not suffer from very strong interferers. First, walls will attenuate signals from unrelated systems significantly. Second, signals originating in the same room are likely to be part of the same communication system, in which case the higher layers of the communication link can avoid interference by separating such signals in the frequency, spatial and/or time domain. Therefore, only limited channel selectivity will be needed. After the (limited) channel selectivity, the signal can be processed through (strongly) non-linear circuits such as limiters to provide the required gain and automatic gain control.

Circuit requirements for a receiver will typically emphasize gain at mm-wave frequencies, wide bandwidths, and low noise figures, with moderate requirements for linearity. For a zero-IF receiver, because of the limited interference provided by the higher layers, it is usually possible to achieve the desired second-order non-linearity by careful design of the mixers and AC coupling in the IF path.

Requirements on the phase noise of the VCO are likely to be relaxed, since the wide channel bandwidths puts the adjacent channels at a large frequency offset. In addition, if the system is completely TDMA based, and therefore effectively single-channel, requirements on the tuning range for the VCO will be relaxed since only process spread, temperature and power supply variations need to be compensated. It will even be possible to clean up the phase noise of the VCO across the full channel with a wide-band synthesizer loop especially for single-channel systems.

Transmitters for mm-wave systems need to generate wide-band signals. Since in many cases, bandwidth efficiency is not the primary design

parameter, and since systems do not have to be dimensioned for minimum interference, requirements on dynamic range and error-vector magnitude (EVM) are likely to be relaxed. Therefore, the emphasis for most transmitter circuits will be on gain, output power and wide bandwidths.

2.3 Implementation in Silicon & CMOS

Traditionally, mm-wave radio frequency (RF) technology has been the domain of expensive chip technologies based on III–V compound materials such as GaAs and InP [5]. These technologies have low yield and limited integration. They are mainly intended for professional and military applications for which the cost-factor is not of much relevance.

Recently, considerable RF performance at mm-wave frequencies has been achieved using low-cost silicon-based SiGe [6] and CMOS [7–10] technologies. The high frequency capacity of silicon based SiGe and CMOS technologies improves quickly. Their unity-gain frequency f_t and maximum frequency of operation $f_{\max}$ have reached hundreds of GHz. Considering that silicon based technologies have replaced GaAs in the low GHz regime except for a few applications (e.g. power amplifiers), they are expected to dominate in the mm-wave frequencies soon.

The advantage of SiGe technology is that as compared to CMOS technology, SiGe has better physical properties, reliable RF models and tools to meet mm-wave requirements. The drawback is that unlike the CMOS technology, SiGe can not cost-effectively integrate the digital baseband on the same chip with RF and analog circuits. Therefore, the radio system needs to be realized in multiple chips instead of a single chip.

CMOS technology has advantages of being the lowest cost option in volume production, and offering high level of integration with RF, analog and digital circuits. Although the RF performance of standard CMOS is worse than that of SiGe, the speed of CMOS transistors increases more rapidly. There are enormous world-wide efforts to scale to lower gate-lengths for the mass market of digital microprocessors, digital computation and memory. As a result, the speed of CMOS circuits increases by roughly one order of magnitude every ten years [38]. High power amplifiers implemented in today's 65 nm RF-CMOS technology can produce an output

power level of higher than 10dBm [39, 40], and low noise amplifiers with noise figure of around 6dB can be realized at 60GHz [41, 42].

A fully integrated mm-wave system (RF, analog and digital circuits, or even antennas) in a single chip using a CMOS technology will bring many benefits, for example:

- The single-chip integration will result in a smaller footprint, and reduce the cost of multi-chip packaging and testing.
- With the aid of integrated advanced digital signal processing (DSP), there can be auto-tuning and digital calibration in the RF front-end. The functions may include I/Q matching calibration, filter bandpass tuning, VCO/PLL calibration. In this way, the RF front-end will be robust against process, voltage and temperature (PVT) variations.
- Self-testing of a full transceiver can be carried out in the loop-back mode automatically, which will avoid expensive RF test equipment and cost.

2.4 Conclusion

Millimeter-wave frequencies (30–300GHz) offer many new products and services such as multi-Gbps radio at 60GHz, automotive radar and mm-wave imaging, thanks to the high frequency and large bandwidth available at these frequencies. High data rate radio links with high bandwidths at high frequencies (60GHz) require electrically large antennas ($\gg \lambda/2$) that provide sufficient antenna gain and directivity.

As compared to counterparts at lower frequencies, transceiver architectures at mm-wave frequencies have to meet different requirements. In order to achieve a sufficient signal-to-noise ratio, less bandwidth-efficient modulation schemes (e.g. QPSK) become attractive. A TDMA scheme fits with these simple modulation schemes and can reduce interference to adjacent channels. Phased array techniques are attractive to compensate the path loss and alleviate the requirements of RF transceiver front-ends.

Recently, considerable RF performance at mm-wave has been achieved using low-cost silicon-based technologies. CMOS technology has advantages of being the lowest cost option in volume production, and offering

high level of integration with RF, analog and digital circuits. In the next chapters, we will present the design and implementation of 60GHz integrated circuits in a 65nm CMOS technology.

Integrated 60GHz RF Beamforming in CMOS

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