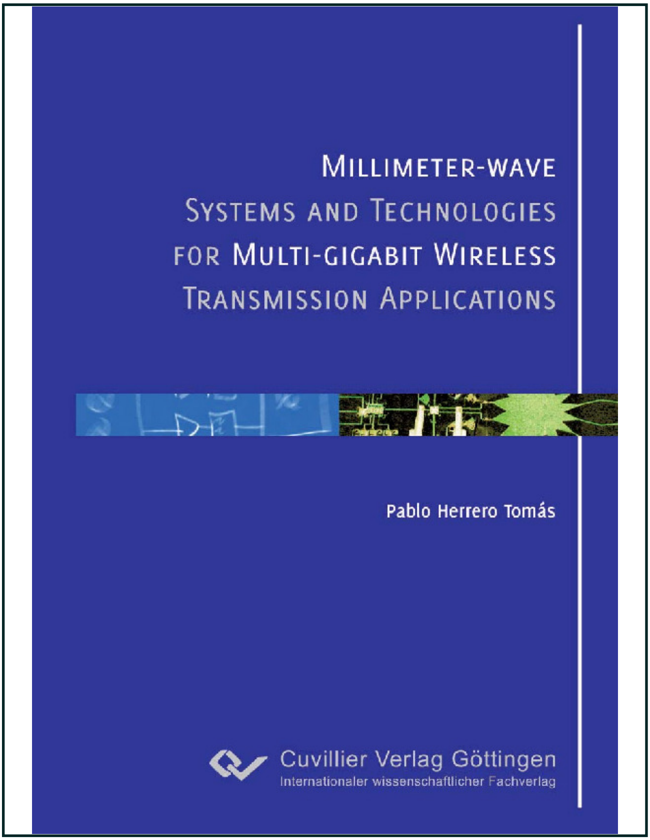
Pablo Herrero Tomás (Autor)

Millimeter-wave Systems and Technologies for Multi-gigabit Wireless Transmission Applications



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1 Introduction

1.1 Wireless Communications

Wireless technology has changed our world considerably. Devices which can communicate without the use of cables are everywhere around us, for every possible application that any person can imagine. Wireless technology is not only used in communications, but also in other applications such as radar, any kind of sensing, or product identification. The use of this technology is becoming astonishly cheaper and easier.

As wireless technology evolves, new challenges have to be faced. A wireless system needs to transform and process the source data so it can be transmitted through the air and successfully received. Hopefully, with no errors and with the highest speed as possible. It is precisely in this area where research efforts need to be invested so wireless systems can continue being even more useful, more popular and more profitable.

If one stop and thinks about how the wireless market and technology has evolved during the last years, one clear conclusion can be drawn: future systems will operate at higher frequencies and will have higher bandwidth than the current ones. This directly leads to a faster data rate. The question is how fast it can go. Predictions (and demands) say that a data rate of 10 Gbps is not so far away and that it will be widely spread by 2015 [1]. This data rate is by one order of magnitude higher than the commercial systems currently available. Maximum currently available throughput could be around 300 Mbps using MIMO (Multiple Input Multiple Output) technologies [2].

1.1.1 Millimeter-wave frequencies and applications

Since the very beginning of wireless technology, basic improvements focused on creating a system as reliable and as fast as its wired counterparts. Probably the latter is the case which receives more attention, as it increases popularity and improves the market entry level. The end user always demands more bandwidth for new multimedia applications. Several strategies can be adopted to increase the data rate of a wireless system. One strategy could be to increase the spectral efficiency of the systems. This would mean using high order modulation schemes, or MIMO oriented solutions increasing therefore the data rate.

However, there is a complexity and cost limit in terms of hardware (i.e. number of antennas, output power). Another solution could be to increase the carrier frequency of the system, with the corresponding increase of the bandwidth [3]. This solution can help to improve the data rate of the systems. At the same time, by moving systems to higher frequency bands, the current problem of an overcrowded spectrum can be alleviated. Moreover, increasing the carrier frequency enables the potential for circuit miniaturization and integrability. Thus, this solution reveals as the natural evolution of wireless systems.

This explains the heavy research being carried out in the last five years in the so-called millimeter-wave range. The focus has been particularly put into frequency bands such as 60 GHz [4, 5] or 122 GHz [6, 7] due to their particular propagation characteristics. These bands are in attenuation peaks of the EM (Electromagnetic) spectrum, making it a good choice for short range communication systems such as WLANs (Wireless Local Area Networks) and WPANs (Wireless Personal Area Networks) or sensing, respectively. The new allocated bandwidth available in these frequency bands makes them appropriate for applications which need multi-gigabit data rates. Two applications of millimeter-waves became very popular, gigabit wireless communications and sensing.

Multi-gigabit wireless access is attracting a great deal of interest for satisfying the tremendous demand of new multimedia applications. Wireless HDMI (High Definition Multimedia Interface), new HDTV broadcast signals, Video On Demand schemes and Portable Personal Area Devices (like wireless hard disk drives) are examples of applications that would certainly demand a gigabit-like data rate. For example, the transmission of a TV program with several channels in High Definition would require up to 10 Gbps [8].

Another application which can also benefit from this frequency increase is sensing or radar. Particularly, automotive radar is a very popular application of millimeter-waves. The high frequency allows very narrow beams and small devices that are mandatory in a radar of this sort [9, 10]. 77 GHz commercial sensors are already available developed by Bosch [11], Toyota or Macom, and high-class cars such Mercedes-Benz, Audi or BMW have this as an optional component. Currently these sensing systems are moving from autonomous cruise control and crash warning to real pre-crash reaction. Control systems of the vehicle (throttle, brakes) react when the radar system detects an unavoidable collision. The future concept of these systems is to create a virtual safety belt around the vehicle with multiple sensors, enhancing the current scenario towards the goal of autonomous driving [12]. To achieve this goal, higher resolution radars and better accuracy is required.

1.2 Millimeter-wave systems

Obviously, scaling up to higher frequencies cannot be a zero cost solution. As wireless applications are moving toward millimeter-wave frequencies, physical constraints make new problems arise, which do not necessarily take place in conventional microwave bands. Additionally, the common problems get even worse. The circuit or system designer is faced with a new and unique set of challenges to deal with in order to use this portion of the spectrum successfully [13].

Differences in economic factors, manufacturing capabilities, and even the currently avail-

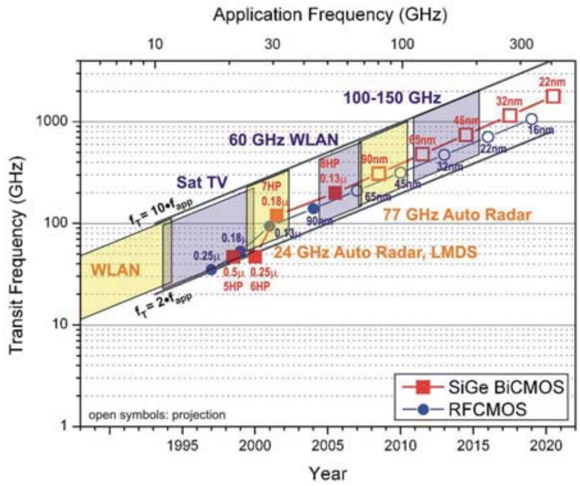

Figure 1.1: Projection of transit frequency for low-cost CMOS processes [3].

able test equipment may force the millimeter-wave designer to look for a completely different solution from what would be appropriate for a similar microwave engineering project.

Antenna technology faces a particular problem at millimeter-wave frequencies and it is to overcome the path loss. This loss is considerably higher for example at 60 GHz than at conventional microwave frequencies (almost 30 dB more than at 2.45 GHz). This translates directly into higher antenna gains which need to be implemented on a low-cost basis and with a reasonable size to potentially enter the market. Tied to the antenna, how to connect it with the rest of the system with a reasonable low loss also becomes a problem. At the same time, bandwidths need to be broad enough, so some design effort on antenna structures which can accommodate such broad spectrum is needed.

In this high millimeter-wave range, integrated MMIC (Monolithic Microwave Integrated Circuit) technology based on group III-V elements (like GaAs and InP) has a cost that is far away from being attractive for consumer applications, so the market will probably rely on SiGe BiCMOS and RFCMOS technologies for their devices. Fig. 1.1 shows a prediction of the transit frequency for low-cost CMOS processes, versus technology family and time.

Data shown in Fig. 1.1 has been interpolated using the information available for the previous CMOS families and its performance, supposing that the technology improves in the same way as it has been seen over the last 10 years [14]. From this evolution it can be easily guessed that silicon technology will be available in approximately 5 years or even less for frequencies up to 150 GHz. By this time, suitable system architectures need to be addressed.

1.3 Outline of the thesis

The outline of this Thesis is shown in Fig. 1.2. It addresses the complete top-down process of several fundamental aspects in the design of a complete millimeter-wave system, from the RF point of view.

The target of this research is to explore novel and current structures and architectures for

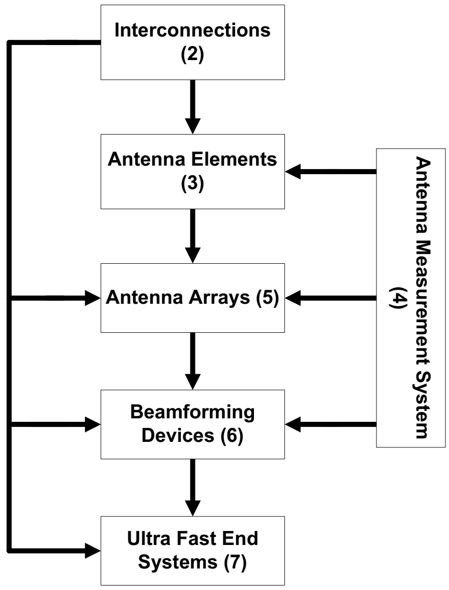

Figure 1.2: Thesis outline.

the next generation of wireless systems, capable of gigabit and multi-gigabit data rates. The thesis provides insight on interconnection structures, antennas and radio front ends, all built on a low-cost technology.

Since antenna and system interconnection is needed throughout the whole thesis, this aspect is discussed in first place. This can be found in Chapter 2, where interconnections for several millimeter-wave frequency bands are analyzed, including a novel structure for D band interconnection and its theory of operation. The interconnections are used in all single element antennas designed in Chapter 3. In this chapter, planar antennas with different radiation patterns and bandwidths, having in mind different applications, are shown. The antennas are accurately measured with the system developed in Chapter 4, a tailor-made setup for the measurement of planar millimeter-wave antennas, configurable for different frequency bands. Chapter 5 addresses the problem of path loss, proposing antenna array structures for millimeter-wave band operation. In Chapter 6, the Quality of Service (QoS) issue at 60 GHz is discussed, proposing beamforming structures to overcome the problem. Chapter 7 includes all knowledge created above, addressing the realization of a complete 60 GHz band system demonstrator with QoS. Chapter 8 will extract some general conclusions of the work and will give an outlook of future research lines.

1.4 Contributions

The main contributions of this research are the following,

- A novel D band microstrip to waveguide transition with low insertion loss is designed and implemented in Chapter 2. With this device, accurate and easy system and antenna interconnections can be made between planar structures and rectangular waveguides. Built on a low-cost basis, it features a loss within 10 GHz of bandwidth of less than 1 dB per interconnect. Such loss is comparable to similar transitions in X band (10 times lower in frequency). An electromagnetic theory not previously reported on the literature which explains and formalizes the coupling mechanism is also presented.

- A broadband planar antipodal dipole antenna for 122 GHz is presented in Chapter 3. The antenna has a very broad bandwidth, enough to cover future applications in this band. Moreover, the antenna is relatively insensitive to low-cost fabrication innacuracies. A redesign of the antenna to cover the full 60 GHz band is also carried out. A transmission line model for the antenna is given.

- A configurable setup for millimeter-wave antenna measurement is proposed in Chapter 4. Using this setup, easy and very repeatable antenna measurements can be made, even in full azimuthal and elevation planes and using both polarizations, which considerably improves state of the art solutions. The setup can be used to measure antennas at V or D band.

- To overcome the Quality of Service issue on the 60 GHz band for High definition video streaming, a Rotman lens is employed to implement a beamforming antenna. Some demonstrators with a swath of $\pm 45^{o}$ are presented in Chapter 6. Such field of view is totally unexplored with a Rotman Lens. In the same Chapter, a multi-reconfigurable beamforming device capable of tilting linear and circular polarizations beams in two different planes is also developed.

- A complete demonstrator for 60 GHz communications with Quality of Service is implemented in Chapter 7. The system employs the above designed antennas and a novel system architecture for the radio design using off the shelf components. The system is configurable for the utilization of different antennas and beamforming devices and can be used as channel sounder to investigate the properties of the 60 GHz band. The front end is capable of selecting different antenna beams in the RF domain, demonstrating the QoS for the first time.