1

Introduction

The rapid convergence of wireless communications systems and digital media has been one of the most exciting developments in electronics during recent years. Increasingly, consumer electronics is the driving force behind technological advance, whereas in the past it was military and space projects. Consumer electronics has become the leading edge of technology because of the potentially huge sales volumes. As the market is extremely competitive, major global companies invest large sums in research and development in order to introduce new products with more features and better performance than their rivals. One of the biggest growth areas has been in mobile internet connectivity through smartphones and tablets, leading to a paradigm shift towards cloud computing, shown by the dramatic growth in mobile subscriptions and internet traffic. 5G heralds a new era in which wireless connectivity reaches everything, with the Internet of Things (IoT) creating a revolution in almost every facet of modern life, including healthcare, smart cities, energy, robotics, manufacturing, retail and the creative industries.

In the business of consumer electronics, it is well known that customers generally get (and, indeed, expect) more features for less money as technology advances. The key to this has been the continual and rapid development of silicon technology, allied with the globalisation of the electronics manufacturing business. By putting more transistors onto a single integrated circuit (IC), clearly a given product will require less ICs and less associated components on a circuit board. Gordon Moore, a cofounder of Intel, predicted in 1965 that the complexity of a chip could be expected to increase exponentially with time for a number of years [1]. This famous prediction has developed into Moore's Law, which is an empirical law that accurately charts technological progress in the microelectronics industry, with the number of transistors on a chip doubling every year. Figure 1.1 shows a graph charting this evolution of Intel microprocessor technology, re-plotted on a linear scale to show the dramatic development of computer technology, and illustrates that we have only recently entered the information age. The impressive milestone of two billion transistors on a chip was reached in 2008 [2].

Microwave and Millimetre-Wave Design for Wireless Communications, First Edition.
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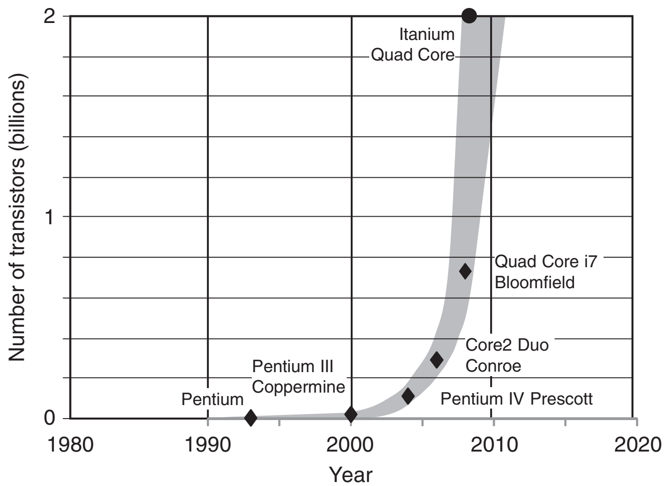

Figure 1.1 Microprocessor transistor count versus year on a linear scale.

1.1 A Brief Timeline of Consumer Electronics

"We only recently entered the information age" is a bold claim that requires substantiation. A worthy method of investigating the claim is to briefly study the history of consumer electronics and develop a timeline of how the main audio, video and communications products have developed. Figure 1.2 shows a simplified timeline of some of the most important developments

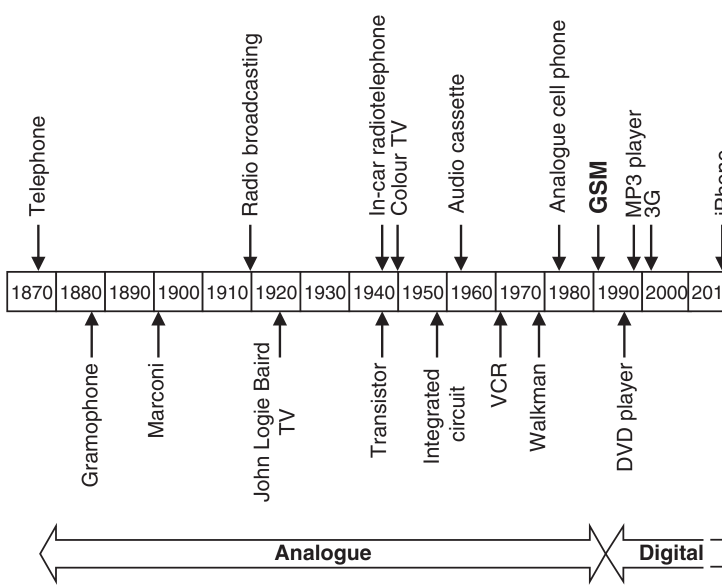

Figure 1.2 A simplified timeline of developments in consumer electronics.

in communications, radio and television. The telegraph came first, with the Cooke and Wheatstone six-wire, five-needle system and the Morse code system being independently introduced in the 1830s in the UK and US, respectively. A number of pioneers had experimented with the speaking telegraph, and it was on 10th March 1876 that Alexander Graham Bell spoke the words "Mr. Watson, come here, I want to see you" to his assistant.

After various pioneering efforts to record audio, including Thomas Edison's cylinder-based Phonograph, in 1887 Emile Berliner patented the disc-based machine (the Gramophone) that that is similar to what we know today. Broadcasting has its roots in Marconi's successful demonstration of radio communications across the Atlantic in 1901. Radio broadcasting became established during the 1920s, and TV started appearing shortly after John Logie Baird's demonstration of an electromechanical television in 1926. In 1928, American inventor Philo Taylor Farnsworth gave the first public demonstration of an all-electronic scanning television system [3]. He was awarded a string of patents, which he later licensed to RCA, which became a giant in the world of TV and radio. The 1950s, 1960s and 1970s witnessed an extensive development of colour television and recording, and the first portable audio products.

The mobile telephone has its origins in Motorola's radiotelephone of 1946. The first automated cellular systems were NTT's in Tokyo in 1979 and the NMT network introduced in Sweden and Norway in 1981. The AMPS system was introduced in the USA in 1983 and the DynaTAC handheld cellular phone was introduced by Motorola, considered to be the first ever handheld phone and now recognisable instantly as the "brick phone". GSM phones were introduced in 1991 – a digital system with greatly enhanced speech quality. Although personal computers were available about a decade before, GSM phones were one of the first consumer products that used digital electronics to perform real-time processing of signals. The 1990s can therefore be considered (debatably) the start of the digital consumer product revolution, with the DVD player (1996) and portable MP3 player (1998) appearing in the same decade. The iPhone was launched in 2007 and, in the short time since, smartphones and tablets have become an almost indispensable part of modern living, being most people's main portal to the internet, with awesome functionality that includes multi-band cellular and internet connectivity, voice-directed navigation, multimedia playback, games, augmented reality, and so on.

1.2 The Electromagnetic Spectrum

Electromagnetic waves are vital to almost all communications systems and modern consumer products. Radio waves, infrared, visible light, ultraviolet (UV) radiation and X-rays are all forms of the same phenomenon of electromagnetic wave propagation. Some of the most important frequency bands and applications of the electromagnetic spectrum are shown in Figure 1.3. This is, once again, on a logarithmic scale: X-rays have a frequency around a billion times the frequency of a mobile phone radio signal. Of course, not all these frequencies can be generated easily (if at all) by conventional transistor-based electronics. High-power microwaves, for example, are generated in a magnetron for some applications. Light, for optical storage and communications, is generated by a laser.

Some of the most common frequencies and applications are listed in Table 1.1. Wavelength (λ) is inversely proportional to frequency and, assuming free space propagation, the relationship $c = f\lambda$ can be used, where c is the speed of light *in vacuo* (3×10^8 m s^{-1}). For radio

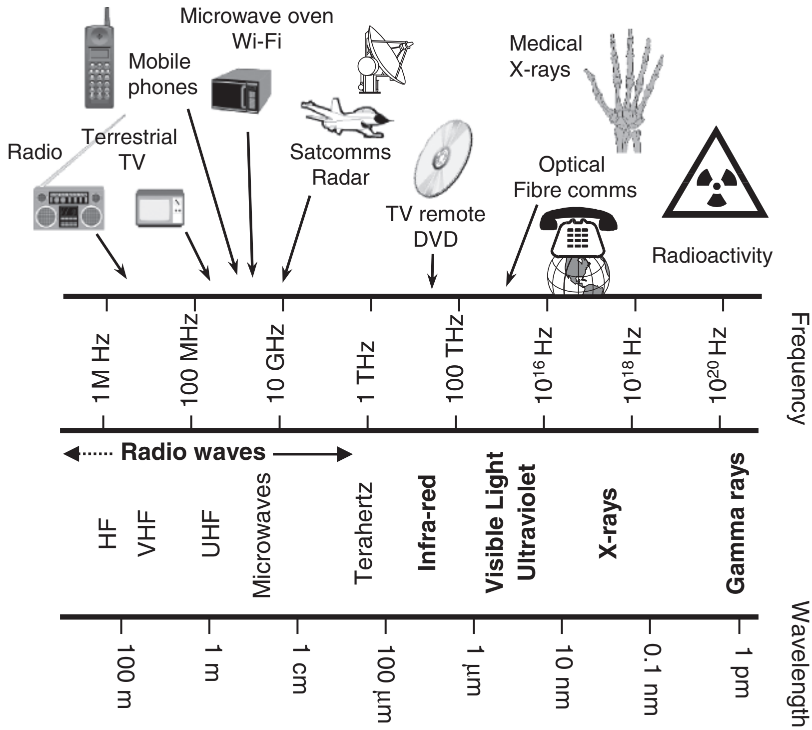

Figure 1.3 Frequency, wavelength and terminology for various applications of electromagnetic waves.

Table 1.1 Example frequencies of some common systems.

Frequency	Application
0.5 to 2.6 MHz	Medium wave AM radio band
220 MHz	Digital audio broadcasting
500–850 MHz	UHF TV band
850, 900 MHz and 1.8, 1.9 GHz	GSM mobile (cell) phones
2.2 GHz	3G mobile phones
2.45 GHz	Microwave ovens, Bluetooth, 802.11b/g/n wireless LANs
10 GHz	Military radar
11–12 GHz	European satellite TV
60 GHz	802.11ad gigabit wireless LANs
77 GHz	Cruise control in some cars
198 THz	Long-distance fibre communications
333 THz	TV infra-red remote control
430 THz	Red light
1 million THz	X-rays in hospital

waves, the wavelength is large and the macro effects of electromagnetism and wave propagation readily apply. At the other extreme, light has a typical wavelength of <1 μm and quantum effects start to become important: In other words, the packet nature of light – the existence of photons – must be taken into account.

Radio transmission is used for hundreds of applications, and modern society could not exist without these radiofrequency (RF) systems. The frequency bands ranging from 100 kHz up to 100 GHz (100 000 MHz) are already extensively used for radio, TV, mobile telephones and the cellular network infrastructure, Wi-Fi, private mobile radio, satellite TV and data links, along with a whole host of other communications systems. Frequencies from 100 GHz to 400 GHz are already starting to be allocated to new systems, as the lower frequencies become congested. In addition to communications, the radio spectrum has slots allocated for other uses, such as radar, navigation, radio astronomy and remote-sensing. Remote-sensing is very important for the environmental monitoring of problems such as the hole in the ozone layer and the destruction of tropical rainforests, while microwave systems are very important because of the need to penetrate cloud cover.

A key principle in radio communications is that antennas, which convert electrical currents into radio waves (or vice versa), need to be of a size comparable to a wavelength. This, essentially, is why high-frequency signals are used for wireless communications – the antennas must be of a practical size. In all cases, the choice of operating frequency is governed by a range of factors, including bandwidth and range required, transmitter power available, propagation loss, antenna gain, cost of the equipment and licensing. The gain of an antenna is a figure of merit that describes how effectively it concentrates power into a desired direction, that is, towards the receiver(s). A perfect omnidirectional antenna spreads power out equally in all directions, as illustrated in Figure 1.4(a), and has a gain of 0 dBi (dBi = decibels relative to the *isotropic* case). For an idealised point source transmitter, the power would be equally distributed over the area of a sphere ($4\pi r^2$, where r is the distance from the transmitter) giving rise to what is known as spreading loss, with signal strength falling as $1/r^2$. Even in a broadcasting application, such as terrestrial TV, if the transmitter really had an omnidirectional antenna like this, a great deal of its precious RF power would be radiated upwards into space and wasted.

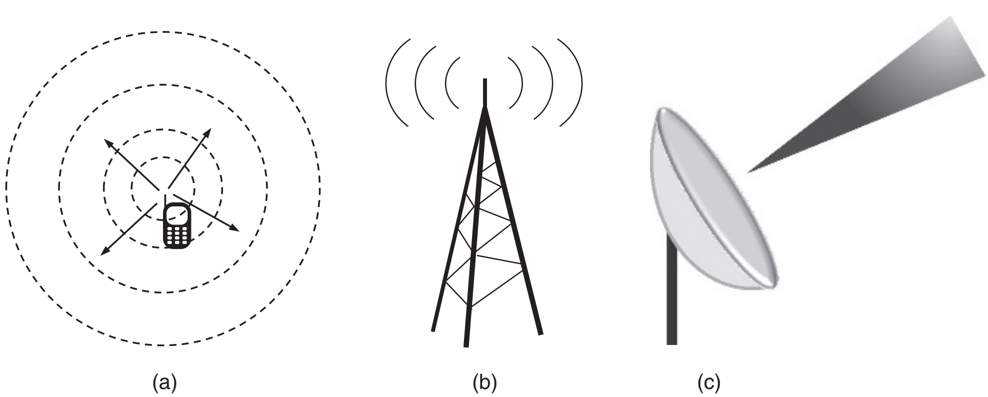

Figure 1.4 (a) Idealised point source transmitter giving omnidirectional coverage. (b) Doughnut-shaped radiation pattern from a typical terrestrial transmitter. (c) Pencil beam from a satellite dish.

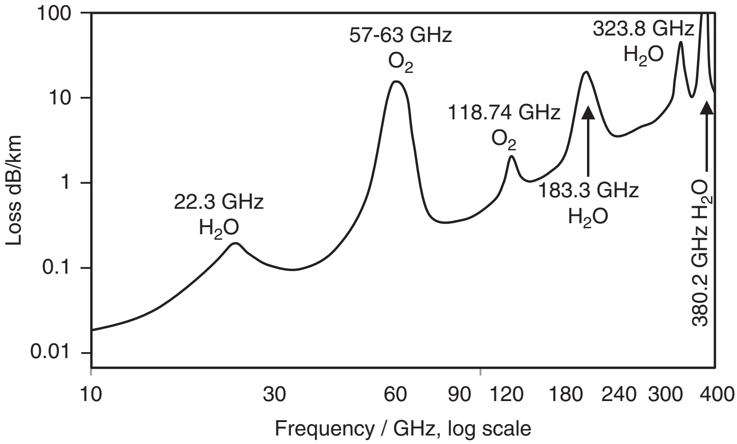

Figure 1.5 Trend of atmospheric attenuation at sea level; see Ref. [4] for data.

Hence, the antenna is designed to concentrate its power in the directions where it is needed – typically the radiation pattern would be doughnut-shaped for a terrestrial TV transmitter, as illustrated in Figure 1.4(b). For direct line-of-sight communications, a parabolic dish has a 'pencil beam' radiation pattern approximately 2–5 degrees wide, as illustrated in Figure 1.4(c), and has high gain of the order 35–40 dBi. Antennas are passive, reciprocal, devices and if an omnidirectional antenna is used for a receiver it will pick up signals equally from all directions, including noise and interference, and so the receiver's antenna gain is equally important.

High-gain antennas are many wavelengths in size, so at low frequencies a high-gain antenna may be unfeasibly large. On the other hand, whilst high-gain antennas are physically small at high frequencies, the propagation loss starts to become more of a problem. Figure 1.5 shows a plot of the atmospheric attenuation (dB km^{-1}) at sea level of a signal [4]. The loss is dominated by the effects of water vapour and oxygen: water vapour causes the steady increase in loss as frequency increases, as well as peaks at 22.3, 183.3 and 323.8 and 380.2 GHz due to rotational modes of the asymmetric H_2O molecule; oxygen absorption causes the peak at 60 GHz (which actually is formed from a number of lines between 57 and 63 GHz) and a clear line at 118.74 GHz. A further complication is the need to consider the intermittent attenuation caused by rain, fog, clouds and dust, particularly at frequencies beyond 10 GHz. For communication that is not line-of-sight, it is also necessary to account for attenuation and blocking due to natural and man-made obstacles – in those situations, low frequencies give a diffraction advantage. This is sea-level data and the atmosphere actually has a number of distinct layers. In mobile systems, the propagation characteristics can change rapidly with time, and the Doppler effect needs to be accounted for in the case of moving vehicles. Propagation effects are a highly complex issue that is covered in more depth in Chapter 14.

1.2.1 Spectrum Licensing and Standards

In order to prevent different users interfering with one another, the use of the radio spectrum is carefully regulated by government agencies (such as the FCC in the USA and OFCOM in

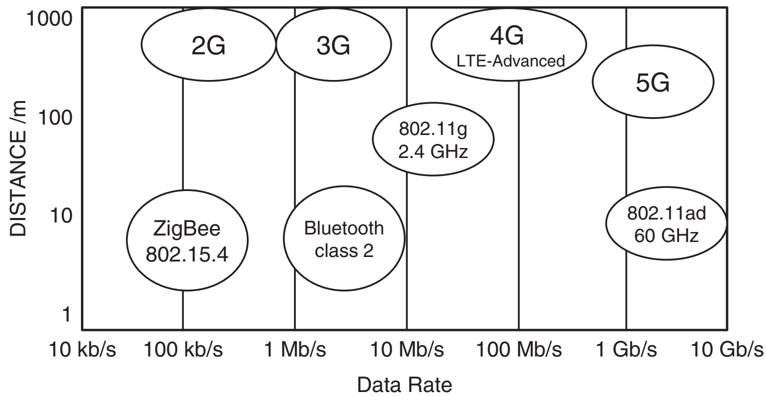

Figure 1.6 Various wireless communications standards compared.

the UK) and international bodies such as the International Telecommunications Union (ITU). These bodies issue licences to bona fide users, seek out unauthorised users, and conduct extensive consultations with stakeholders before allocating new frequency bands. There are many different types of licence, depending on the transmission frequency and application. Frequency allocation charts are available to download, and the number of different bands that have been allocated for diverse purposes is amazing. Wallcharts of ITU allocations are available (e.g., www.cedmagazine.com has a free pdf file) but there are so many allocations that the chart would be unreadable if reproduced here.

To ensure that radio equipment and consumer products are compatible, there is a tireless effort by standards committees to define the hardware and software specifications for different applications. Modern communications systems are so sophisticated that these documents run to hundreds and hundreds of pages. The Institute of Electrical and Electronics Engineers (IEEE) standards are particularly important; for example, the IEEE 802.11 wireless LAN standards were key to the rapid adoption of Wi-Fi around the world. Figure 1.6 shows various IEEE and other wireless communications standards compared on a range versus data rate graph.

1.3 Industry Trends

A general background to the electronics industry as a whole is important in the study of modern wireless communications systems. At the heart of the industry's success is nanometre-scale silicon technology, particularly CMOS technology, capable of realising sophisticated system-on-chip products. In addition to this, many microwave and millimetre-wave systems, and the photonic systems that make up the core network, require specialist compound semiconductor devices such as GaAs, GaN and InP devices. This has led to a great deal of research and development in the area of miniature systems integration, including multi-chip modules, system-in-package and antenna-in-package techniques (these are described in Chapter 16). Silicon and SiGe technology has started to challenge many of the traditional III–V markets and is rapidly opening-up the millimetre-wave part of the spectrum for consumer applications such as 60 GHz wireless networks.

The microwave industry has changed dramatically as consumer-oriented products such as cellular mobile, Wi-Fi, Bluetooth and GPS systems, amongst others, have become mainstream. The volume of this side of the industry is absolutely vast; for example, one billion Android smartphones and nearly 200 million iPhones were sold in 2014. This immense scale has changed the way the industry operates. To be a world leader, a company must have the resources to meet this huge demand. Typical silicon fabs with state-of-art capability cost more than US$3 Bn, while a large display factory, required to process 30 000 glass panels per month, each as large as 2 × 3 metres, typically requires an investment of US$5 Bn. Such a factory will require exceptionally good supply chain management, and often suppliers will be housed on-site in order to keep things running smoothly. The scale of mass production of consumer electronics in China is well known, and there are already signs of the industry entering a new phase of globalisation. For example, at the time of writing Foxconn was planning to invest in 12 new assembly factories in India, potentially creating one million jobs.

This immense scale of the consumer electronics industry, which drives a great deal of microwave and millimetre-wave development, has led to new ways of the industry building critical mass, including IP licensing, joint ventures, alliances, mergers and acquisitions. Fortunately, the industry has largely learned the importance of cooperation on wireless standards, with bodies such as the 3GPP, IEEE and ITU playing a vital role. Electronics is already found almost everywhere and has transformed our lives in many ways, and yet there is a further revolution underway in 5G+ communications, the internet of things, machine-to-machine communications, augmented reality and telepresence, to name a few. Without standards, the vision of everything being connected seamlessly to the Cloud will not be achievable.

The scale of the industry and the spectacular pace of change have given tremendous importance to intellectual property and branding. The value of a brand has become more and more about the user experience and even emotional attachment and loyalty. This has dramatically increased the importance of industrial product design and consideration to the human–computer interface. The style and ergonomics of the product are often a key differentiator in the market place, since the electronics inside is comparable. The skill of the product designers lies in exploiting new materials and manufacturing processes to create a stylish design that is economical to produce. Design-for-manufacture (DFM) and design for the environment (DFE) are important themes of this activity. As consumer products are replaced so quickly, designers need to consider how the whole ensemble of electronic and mechanical components can be assembled quickly, for low production costs, and later disassembled for the efficient recycling of key parts and materials. Electronic waste and protecting the environment are areas where government legislation is crucial to the long-term sustainability of the industry.

1.3.1 The Multidisciplinary Nature of Modern RF Engineering

A state-of-the-art integrated circuit is more complex than the whole US road network. It is not difficult to justify the claim, therefore, that electronic engineering is one of the most challenging careers of all, and engineers have to cope with exceptionally rapid technological change. But at the same time, it is also one of the most exciting and fulfilling careers – one only needs to read *IEEE Spectrum* regularly to know that electronic engineers are capable of amazing feats of technology that can dramatically improve our lives through impact in the fields of healthcare, energy, communications, transport, science and space exploration.

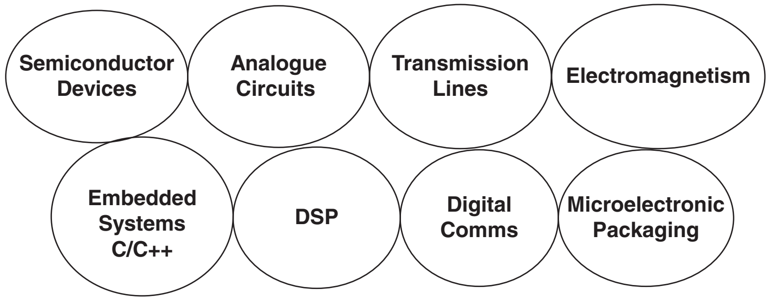

Figure 1.7 Aspects of modern RF engineering.

Microwave and millimetre-wave engineering was, for many years, a niche area in the realm of electromagnetics, transmission lines and the Smith chart, sometimes unfairly referred to as a ‘black art’. As digital techniques have advanced, the RF engineer has needed to develop a much wider range of skills, as illustrated in Figure 1.7, with at least a basic understanding of topics from semiconductor physics through to digital electronics:

Semiconductor Physics: RF engineering uses some of the most advanced semiconductor and quantum devices, because achieving low noise and high power at these frequencies is highly challenging and often beyond the capability of regular devices. RF engineers need, therefore, to be conversant with the underlying physics in the device to make informed design choices.

Analogue circuit design: Twenty years ago, a monolithic microwave integrated circuit (MMIC) amplifier could be designed with two transistors and a few inductors and capacitors to match the transistors to 50 Ω. Now, the radiofrequency integrated circuit (RFIC) designer has to make use of the full range of analogue circuit design skills to reduce current consumption and chip area, and realise complex circuits and subsystems with adaptive control loops to maximise performance.

Microelectronics and packaging: The integration of high-frequency analogue and digital circuits has pushed integration levels and packaging technology to new extremes. Twenty years ago, RF designers might be using single transistor diemounted onto specialist substrates. Nowadays, they are more likely to encounter 3600-pin ball-grid array (BGA) packages that have pushed printed circuit board and assembly technologies to the limit.

Digital communications: The close integration of digital signal processing (DSP) with RF transceivers makes it impossible to work effectively in a team without an understanding of IQ modulation, orthogonal frequency division multiplexing (OFDM), sigma-delta modulators, and so forth. For example, power amplifiers need to be designed to cope with complex varying-envelope signals that maximise spectral efficiency; they cannot be designed in isolation from the digital communications engineers.

Embedded systems design: Modern RF transceivers use extensive digital control for a range of functions. Without the ability to programme in C or a similar language, the RF engineer will be unable to get a chip-set evaluation board or (for example) a ready-made ZigBee or Bluetooth module to work.

1.3.2 Business Matters

The electronics business is extremely competitive; customers demand better and better products every year and expect the price to fall. The need for standardisation sometimes makes it difficult to introduce a new product without extensive industry-wide consultations; format wars such as VHS versus Betamax, Blu-Ray versus HD-DVD, and 8 mm versus VHS-C can be extremely costly and damaging. Competing companies might lower their prices below an economically viable level to encourage consumers to adopt their standard. But sooner or later there have to be winners and losers, and sometimes it is the technically superior technology that loses. Fortunately, with wireless communications standards there is some government control because of spectrum regulation: Thanks to the tireless efforts of engineers on committees, there is a high degree of standardisation. However, this is never a straightforward process as licensing fees for crucial patented technologies might require extensive negotiation.

Whilst consumer electronics is a very competitive business, it can also be extremely profitable. In 2014, the top ten consumer electronics companies were, in alphabetical order; Apple, Canon, Hitachi, HP, Nokia, Panasonic, Philips, Samsung, Sony and Western Digital. The top five smartphone brands were Samsung, Apple, Xiaomi, Lenovo and LG. Apple, the most valuable brand in the world at the time of writing, had sales of US$ 183 Bn and a net income of almost US$ 40 Bn in 2014 [5]. There are other familiar brands, such as Motorola, Dell, LG, Pioneer, Sanyo, Sharp and Toshiba. Some companies are well-known as IC suppliers, including Intel, AMD, Qualcomm, TI, MediaTek, Hynix, Micron, ST, Broadcom, Renesas, Infineon, NXP, Nvidia, Fujitsu and Qorvo. Some of these companies do not actually fabricate any ICs, but there are a number of other companies, including TSMC, UMC, GlobalFoundries and SMIC, which specialise only in fabricating ICs for customers. There are many big companies (e.g., Foxconn, Pegatron and Flextronics) that focus on carrying out electronics manufacturing for the aforementioned global-brand companies. There are many other companies, including Inventec, Quanta Computer, Compal, Elite, WKK and Wistron, that design and manufacture products which are then badged by other companies with their own branding for retail. There is an increasing trend for companies based in China and South East Asia to develop their own brand in the retail market place, with companies including Huawei, ZTE, Lenovo, HTC, Haier, Changhong, TCL, Asus, Panda Electronics, Ningbo Bird, Skyworth, Amoi, SVA, Xiaomi and BenQ amongst those leading the way. What all this highlights is the fact that the global electronics industry is vast (it is estimated to be worth US$ 600 Bn per annum) and relies on a number of different business models, forming a sophisticated network:

Vertically integrated company: The model where a large company makes everything from the semiconductor devices to the branded consumer products.

Contract manufacturer (EMS): A company that concentrates solely on providing an electronics manufacturing service for its customers.

OEM: There are three meanings in use, but in the context used here an original equipment manufacturer produces its own branded products which include components and sub-assemblies from other companies.

ODM: An original design manufacturer designs and manufactures a product that is then sold under another brand name; this is often referred to as ‘badge engineering’.

Chip manufacturer: A company that specialises in designing sophisticated high-value ICs and manufactures them for sale as components.

Foundry: A company that carries out semiconductor manufacturing for customers but does not design products of its own.

Fabless design house: A company that specialises in designing ICs and supplies them as components, but subcontracts out the chip manufacture to a foundry.

Chipless design house: A company that has design techniques that are sufficiently novel for other companies to want to pay to use them in their own chip designs. The UK-based company ARM™ is a good example of this; ARM’s processors are used in a vast number of consumer products but they supply the design IP, which is then integrated within a larger system-on-chip by the customer.

Material, component and sub-assembly suppliers: Companies that specialise in supplying into the businesses that manufacture electronic products. Sometimes these are household names due to the breadth of their activities (e.g., BASF, 3M, Corning and DuPont), but usually these suppliers operate entirely on a business-to-business (b2b) basis and are not well known outside the industry.

Distributor: With a vast range of products available, distributors provide a key intermediary service between suppliers and customers, giving a broad product portfolio, independent advice and technical support.

Value-added reseller: In the context used here, this model refers to a systems integrator that takes wireless equipment and combines it with other hardware and software to provide a high-level product solution. With mobile and wireless systems having a profound impact in new areas such as retail, commerce and the creative industries, this is a valuable service for companies that do not wish to become involved in technical details but instead want a turn-key solution for their business needs.

These categories are well known for the general electronics industry, whilst in the specific case of the telecommunications industry there are additional company categories relating to the manufacture, installation, operation and marketing of the internet and telephone networks. The internet itself, comprised of a huge conglomeration of networks, is operated by a variety of telecommunications companies at the core and access network levels. Mobile network operators (or carriers) own specific cellular network infrastructure and offer services to customers. There are also virtual network operators that buy air time in bulk and sell packages with a distinct retail brand. At another level there are internet-focused companies such as internet service providers and major web site companies, such as social media sites, that operate numerous large data centres in order to meet the demands of more than a billion customers in some cases.

1.4 Forms of Wireless Communication

A wide variety of forms of wireless communication has evolved since the first demonstration of wireless telegraphy by Guglielmo Marconi [6]. In terms of purpose and physical location of the terminals, wireless links can be classified as point-to-point, point-to-multipoint, broadcasting, or mesh networks. In the following sections, some of the key distinct types of communications systems are described, chosen as examples of the main approaches for wireless communication.

1.4.1 Terrestrial Television

All around the world, the analogue TV system has had to make way for digital systems. The analogue TV standards, NTSC (National Television System Committee), PAL (Phase Alternating Line) and SECAM (Séquentiel couleur à mémoire) are rapidly being confined to history. Digital TV makes use of powerful video compression as well as sophisticated modulation and coding schemes to reduce the bandwidth of the transmitted signal. Standard-definition digital TV signals actually occupy a similar bandwidth to the previous analogue systems (e.g., around 8 MHz bandwidth for PAL). A fair question is, then: why go to all this trouble, when the analogue system had been working very well for around 70 years?

The need to move to digital signals to transmit more TV channels was dictated by analogue signals being sensitive to propagation effects and interference. With the power density of the radiated wave falling off as $1/r^2$, a simple calculation shows that in theory a single transmitter antenna could comfortably cover the whole of the UK or a typical State of the US. However, the curvature of the earth means that there is a *radio horizon* which is determined by the height of the transmitter (TX) and receiver (RX) antennas and the radius of the earth. This is given by $\sqrt{17h}$ km [7], where h is the effective antenna height in metres. This is why the transmitters are mounted on tall towers and situated on hills where possible. A 300-metre transmitter height gives around 70 km radio horizon, so the Crystal Palace transmitter, for example, serves all of London. The Crystal Palace transmitter's effective isotropic radiated power (EIRP) is of the order of one megaWatt. The actual power output is less than this, but it is the effective value, which takes into account the transmitter antenna's gain, that determines the signal strength at the TV receiver antenna.

Figure 1.8 shows a stylised map of the main transmitter sites in the UK for UHF TV. There are many other, smaller transmitters or repeaters required to fill in gaps in the coverage that are caused by blocking of hills and buildings. For example, in the London area alone there are about 50 low-power transmitters in addition to the main Crystal Palace one. With analogue signals, receivers are very sensitive to interference; 'ghosting' is a clear visual indication in analogue TV of how a receiver is affected when it receives two components of the same signal from different paths. The ghosting is caused by the small but noticeable difference in the time that it takes each signal component to reach the receiver. To avoid this interference, with analogue TV it is necessary to ensure that adjacent transmitters use different radio carrier frequencies. The frequency allocations and the coverage must be carefully planned. In the UHF band, some diffraction occurs around buildings and even around the tops of hills because

Figure 1.8 The UK's main terrestrial TV transmitter sites.

of the fairly long wavelength of the signal (500 MHz in free space gives 0.6 metre wavelength) but, even so, repeaters are used to fill in poor coverage areas such as valleys where the main transmitter signals cannot reach. The signals from a non-adjacent transmitter with different coverage area can be on the same frequency because of the physical separation; normally, the signals simply do not reach far enough to interfere. However, sometimes the atmospheric conditions can make a signal travel further than normal by refracting (bending) it past the normal horizon. Then, non-adjacent transmitters can interfere; for example, in Kent (in the South East of England) it was sometimes possible to receive TV signals from Belgium in unusual weather conditions.

The need to use many different frequencies in the analogue system to avoid interference, unfortunately, leads to a very inefficient use of the precious UHF spectrum. This is the main reason why digital TV is now dominant. As an indication of how much more efficient the digital TV system is, note that in the UK there were only five terrestrial analogue TV stations, even after many years of technical development: however, within a few years of its introduction to the UK, digital terrestrial TV offered more than 50 stations, even before the analogue system was switched off.

1.4.1.1 Digital Terrestrial TV Formats

On December 11, 2006, the Netherlands became the first country to switch off analogue and move entirely to digital TV broadcasting. The number-one advantage of digital TV is that more channels are possible, but making this happen is a major feat. The first step is to use video data compression standards such as MPEG-2. The second key technology involves the highly advanced coding and modulation techniques that are used. There are four major digital terrestrial TV standards around the world at the time of writing, with the following main deployments:

ATSC: Advanced Television Standards Committee
USA, Canada, Mexico, South Korea
The main terrestrial version of this standard uses a modulation scheme called 8-VSB (vestigial sideband), which is an advanced form of ASK, using eight levels of amplitude and spectrum shaping to achieve high spectral efficiency.

DVB-T: Digital Video Broadcasting (Terrestrial)
Europe, Russia, Africa, India and Asia, Australia
DVB allows for a range of different signal formats for different broadcasting systems: e.g. DVB-S for satellite, DVB-C for cable, DVB-H for handhelds.

ISDB: Integrated Services Digital Broadcasting
Japan, South America, Botswana, Philippines

DTMB: Digital Terrestrial Multimedia Broadcast
China, Hong Kong, Macau

DVB-T, like many other wireless communication standards, uses orthogonal frequency division multiplexing (OFDM). The purpose of OFDM is to combat the effects of multipath propagation. Figure 1.9 illustrates, simplistically, how multipath propagation leads to spreading of the data signal, placing a limit on the maximum data rate because of inter-symbol interference (ISI). In practice, there will rarely be just a few distinct signal components, and it is necessary to analyse the channel statistically and refer to a more continuous effect of *delay spread*. In OFDM, the digital data is split up and sent in parallel using a closely packed block of thousands of RF carriers, each with a much lower individual data rate, as shown in Figure 1.10. This type

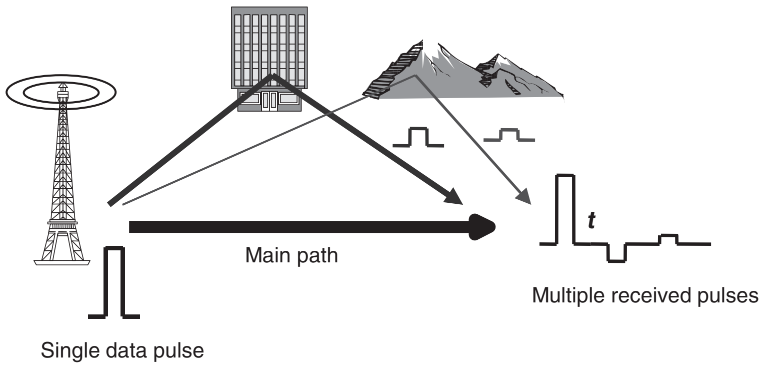

Figure 1.9 Illustration of multipath propagation and its limiting effect on symbol rate.

of signal is more resilient to the multipath fading than a single carrier carrying a high data rate. The multiple carriers are generated entirely within the realm of digital signal processing (DSP) using a fast Fourier transform (FFT), as discussed in Chapter 15. Coded OFDM (COFDM) employs a coding scheme to recover lost data when any carriers are lost due to the multipath propagation. Because these digital signals are much more resilient to interference than the old analogue signal formats, much more efficient use of the spectrum is achievable.

1.4.2 Satellite Communications and Broadcasting

Arthur C. Clarke famously proposed the use of geostationary satellites for communications in 1945 [8, 9]. For a geostationary satellite, by setting the altitude to 35 786 km, the spacecraft naturally orbits the Earth at exactly the same angular velocity as the rotation of the Earth on its axis, appearing therefore to be stationary in the sky. To achieve this, the satellite must be orbiting in a plane perpendicular to the Earth's axis. Hence, in the UK a geostationary Earth orbit (GEO) satellite will be at an elevation of 25.4° (in London) to the South, as shown in Figure 1.11(a). Around the equator, geostationary satellites are directly overhead, but near the

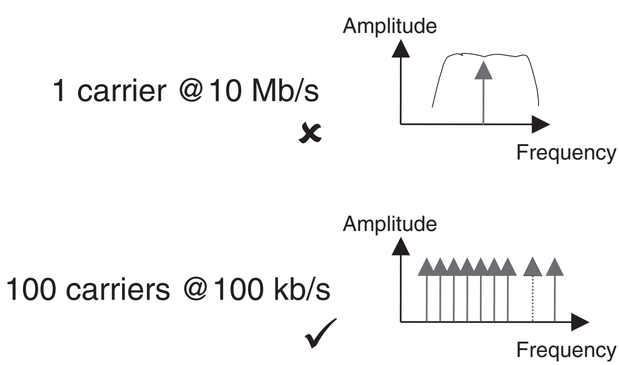

Figure 1.10 The OFDM principle; the data is spread out over many sub-carriers to lower the symbol rate in each.

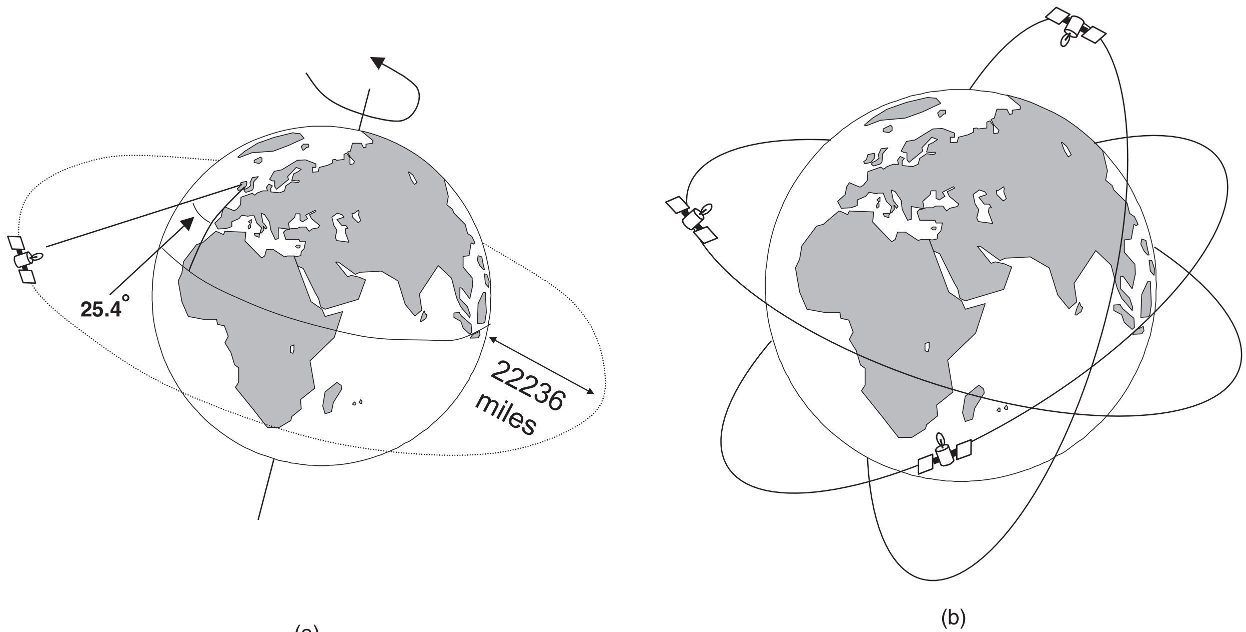

Figure 1.11 (a) TV broadcast satellite in geostationary orbit. The elevation from London is shown. (b) An example LEO satellite constellation.

poles geostationary satellites start to become useless as they are at a very low elevation or below the horizon. A low Earth orbit (LEO), like those shown in Figure 1.11(b), can be useful for these areas and for other applications such as mobile communications as the time delay is reduced, launch costs are reduced, the transmitter power is reduced and the elevation from the horizon is increased. However, as the satellite is moving relative to the Earth and will eventually disappear from view, multiple satellites have to be used to provide a continuous service – the ‘constellation’ used by communications systems such as Iridium™ and Globalstar™ are examples of this. Global navigation satellite systems such as GPS, Galileo, BeiDou and GLONASS use a constellation like this, and the receiver calculates the time difference between the signals received from different satellites in order to determine its position.

Satellite TV broadcasting uses microwave frequencies, much higher than terrestrial TV, because the antennas must have high gain. There is also plenty of spectrum available, allowing many channels. A high-gain antenna is needed for the transmitter on the spacecraft because only solar power is available, so the transmitter power is severely limited. The narrow beam concentrates the precious transmitter power on the Earth, to the appropriate countries. At the receiver, the signal is extremely weak and a large antenna aperture is necessary. The high gain of the receiver antenna rejects signals from other satellites and background noise from the sky, as illustrated in Figure 1.12. In this way, satellites at different locations in the sky can re-use the same frequencies.

Since, generally, a high-gain antenna must be many wavelengths in size, using microwave frequencies enables a high gain to be achieved with reasonably small dishes (e.g., ca, 60 cm for a domestic satellite TV dish in the UK). This is also critical for the satellite: the dish needs to fit inside the nose of the launch rocket (although, in exceptional cases, folded antennas have been used, deployable once the spacecraft is in position). In Europe, frequencies ranging from 10.7 to 12.75 GHz are used for satellite TV. To receive signals on the ground, a dish with a feed is first required to collect the signal. The dish part is used to reflect the electromagnetic power and focus it onto the feed. The signals are so weak, because of the long transmission distance and low satellite transmitter power, that there must be a direct line-of-sight between the receiver dish and satellite. The feed collects the signal and sends it to a low-noise amplifier (LNA)

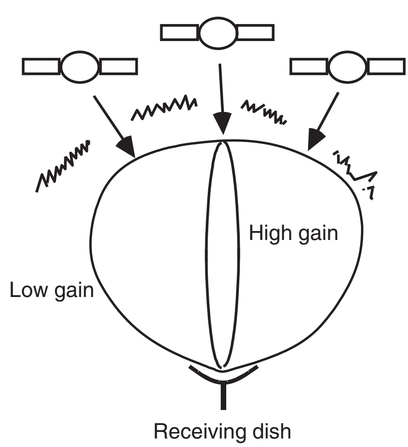

Figure 1.12 Satellite dish beam-width; low- and high-gain antennas compared.

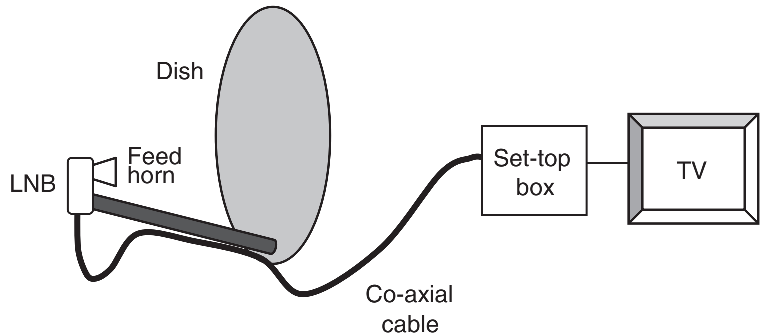

Figure 1.13 Components of a satellite TV installation.

that must be mounted on the dish in order to amplify the weak received signal immediately. After amplification, the signal is frequency-converted because microwave cable is expensive and has a high loss. For example, if the microwave signal were sent directly into the lounge of the house, the 30 feet (approximately) of cable required would be expensive and the loss of the cable would be so high that the signal would disappear into the noise. By first amplifying and then converting the microwave signals down to approximately 1–2 GHz, a much cheaper coaxial cable can be used and the loss is lower. The 1–2 GHz signal is then fed down a cable into the 'set-top box' (STB) where all the complicated signal processing takes place. The unit that amplifies and downconverts the signal is mounted on the dish close to the feed to avoid losses, and is known as the 'low-noise block' (LNB). The components of a typical satellite TV installation are shown in Figure 1.13.

1.4.2.1 Set-Top Box Example

A satellite TV set-top box (STB) serves as a good example of the hardware required to receive and decode digital wireless communications signals. The signal frequencies, modulation schemes and coding vary between terrestrial, cable and satellite systems, and between countries, requiring a sophisticated application-specific system-on-chip (SoC) at the heart of the receiver. The RF engineer's primary contribution is focused on frequency-converting the incoming signal down to an intermediate frequency or baseband signal that this SoC can process. Figure 1.14 shows a simplified block diagram of a typical STB. The heart of the design is a powerful system-on-chip, which is sufficiently power-hungry to require a substantial heatsink. The first functional block in the STB chain is an RF front end that downconverts the incoming signal to analogue baseband (IQ) form. This is followed by a sophisticated demodulator chip that recovers the data stream and performs error correction. This feeds the MPEG decoder, which incorporates MPEG-2 video and audio decoders and a video graphics processor. This chip also includes circuitry to handle the user interface, a wireless network connection, and a wide range of interfaces, such as USB.

1.4.3 Terrestrial Line-of-Sight Links

Often, a private point-to-point system is required and satellite systems have some drawbacks such as the size of the dish required, cost and propagation delay. Line-of-sight (LOS)

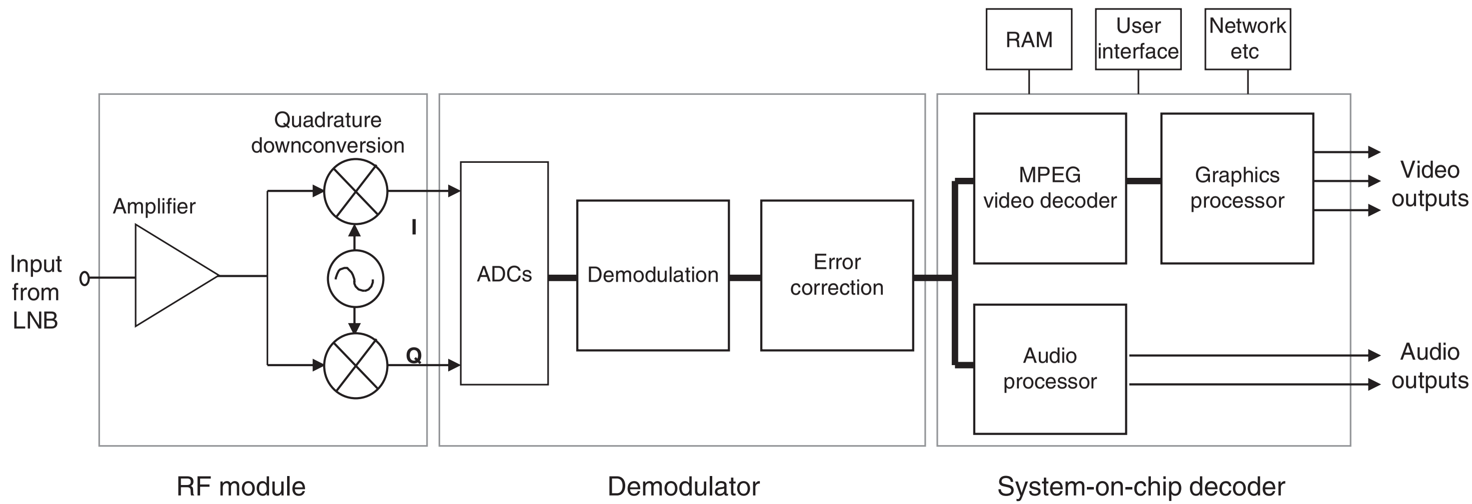

Figure 1.14 Satellite HD TV STB block diagram.

microwave and millimetre-wave fixed links are increasing in popularity as a low-cost alternative to leasing a dedicated wired line for high data rate connections between buildings. The hardware cost has reduced significantly and large bandwidth is available in Ku/K/Ka-band (13, 18, 23, 26 and 38 GHz are common), V-band (the 57–66 GHz band is unlicensed) and E-band (in bands such as 71–76 GHz, 81–86 GHz and 92–95 GHz). Dish sizes are small, especially at V-band and above, and gigabit-per-second equipment can be mounted unobtrusively on rooftops and towers – indeed, the cost of renting suitable space on antenna masts depends on the size. Rain fading can be a major factor constraining the link budget (this is discussed in Chapter 14).

1.4.4 Cellular Mobile Communications

The radio spectrum is an extremely limited resource and, because of the propagation characteristics, only a small part of the spectrum is ideally suited for mobile communications. Low frequencies (up to a few GHz) will readily diffract around buildings and other obstacles and can be received indoors. Higher frequencies, especially above 10 GHz, will travel only along a LOS path. Furthermore, higher frequencies can suffer very high atmospheric loss, especially when it is raining, limiting their use to short ranges. This leaves only frequencies up to a few GHz being suitable for large cells in mobile communications, although higher frequencies can be advantageous when the objective is to have very small, dense cells in urban areas for greater capacity. The bands up to a few GHz are also needed for other applications including TV, radio, GPS, Wi-Fi, Bluetooth and NFC, as well as radar systems, radio telescopes, car alarms, police and emergency services radios, and so forth. As a result, only a limited amount of spectrum can be allocated to mobile services, and network operators have often been required to pay licence fees of the order of billions of pounds just for a few tens of MHz of spectrum. The cellular approach to mobile communications, where many basestations are installed, each serving quite a small area (as shown in Figure 1.15) is essential because:

1. The mobile terminal is battery-powered, so its transmitter power is restricted.
2. The large number of users requires exceptionally efficient use of the spectrum.

In the cellular system, the radio spectrum available for mobile communications can be used over and over again in different cells, as long as they are not adjacent; this is referred to as *frequency re-use*. The radio link is kept to a fairly short range, reducing the handset transmitter power required, and a complex network of interlinked basestations is used to cover a large area. The basestations are linked with optical fibres under the ground, where possible, or with very high-frequency LOS radio links (referred to as wireless backhaul, using frequencies such as 23, 38 and 71 to 76 GHz). The area spectral efficiency (units b/s/Hz/m^2) can be increased by having more, smaller cells: for example, in urban areas where the density of users is higher and propagation more challenging, or when much higher data rates are required, as in 5G.

The first mobile systems were analogue, and the pioneers were in Japan (NTT), Scandinavia (which is why Nokia and Ericsson became leaders in the industry) and the US (Bell Labs and Motorola). In the UK, Racal-Vodafone and Cellnet developed the TACS system which was introduced in 1984. These analogue systems are referred to as the first-generation systems. In mobile systems, the propagation characteristics are challenging; there is rarely a LOS

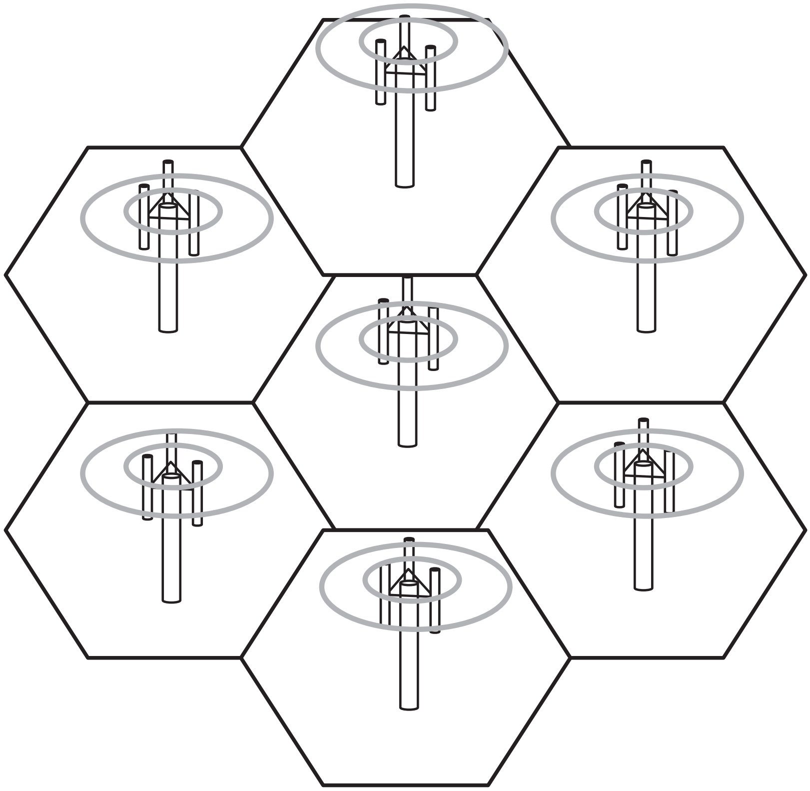

Figure 1.15 A cellular system.

to a basestation and the handset is often indoors, with many obstacles between it and the basestation. With analogue systems it is difficult to counteract all the multipath propagation effects and the voice quality was not good. The early systems used FDMA (frequency division multiple access, where users transmit on different frequencies) which tended to lead to a bulky mobile phone.

Digital systems were introduced in the 1990s. The GSM system introduced in Europe was a result of Groupe Spéciale Mobile, a pan-European standards initiative. This became so successful it was adopted in many countries worldwide, becoming known as the Global System for Mobile communications, which covered more than 80% of subscribers across the world at its peak, before the switch-off started in some countries, from 2015/2016 onwards. These first digital systems, which are referred to as second-generation (2G) systems, gave excellent voice quality, while GSM gave roaming capability in many countries. Different systems and countries use different frequencies, however, which is why there are dual-band/tri-band/etc. phones. The GSM system uses time division multiple access (TDMA) in which different users within one cell can use the same frequency but transmit in different time slots. This enabled the phones to be made smaller and lighter. In the US, the huge size of the country was a barrier to realising a country-wide cellular mobile communications network. The US had different companies and standards operating in different cities and the IS-95 system using CDMA became the most common 2G digital system.

For internet use and e-mailing, the 2G systems were unattractive; the data rate was too low and the system acted like a dial-up service. For this reason, enhanced systems were developed which gave 'always on' connection and higher data rate. In the UK, these included GPRS (general packet radio system) and GSM-EDGE (enhanced data rate system), which are often referred to 2.5G systems. The true third-generation (3G) systems were conceived from the outset as being capable of high data rates and being packet-switched, rather than circuit-switched, for high-speed internet access. The conventional TDMA and FDMA systems were unable to provide this for millions of users. Wideband CDMA (code division multiple access) was the solution. In this approach, many users transmit at the same time and in the same frequency range. However, their signals are all spread out thinly over that frequency range, and the spreading is performed by multiplication with a unique pseudorandom code for each user. In a receiver, only the signal component with the correct code will be correlated with the code in the receiver. By this mechanism, the other signals are all rejected as noise-like. CDMA has proved able to accommodate many more users in a given cell than TDMA and FDMA, although huge technical hurdles had to be overcome.

LTE (long-term evolution) systems started to be deployed in 2009, marketed as 4G or 4G LTE, although it was, strictly speaking, one of a number of pre-4G candidate standards. LTE requires multiple-input-multiple-output (MIMO) antennas in the handset. LTE-Advanced is 4G as defined by the 3GPP (3rd Generation Partnership Project) and was optimised as a purely IP packet-based system for the very high data rates (ca. 300 Mb s^{-1} downlink, up to 8×8 MIMO, OFDM signals) required for routine web browsing on smartphones and tablets. 5G systems aim to significantly reduce latency, so that new applications such as telepresence, augmented reality and cyber-physical systems are feasible, whilst also offering more than Gb per second data rates for very high-speed connections. Another key aim of 5G systems is to achieve new levels of integration of diverse wireless systems, so that the full range of applications – from smart cities and smart grid systems down to small internet of things (IoT) sensor nodes –could be interconnected seamlessly.

Figure 1.16 shows the simplified block diagram of a basic mobile phone. The components in the top half will be immediately familiar; the communications hardware is in the lower half. It might seem illogical that the signal goes from analogue to digital, and then back to analogue, before being modulated onto the RF carrier. The reason is that modulating a pure digital signal onto the RF carrier would lead to a spectrum with many sidelobes. In order to make more efficient use of spectrum the signal waveform envelope has to be carefully shaped, and so a bandlimited analogue version of the digital data is fed into the modulator. The signal is referred to as analogue baseband, usually in Cartesian I-Q form (this is discussed further in Chapter 2).

1.4.5 Wireless Indoor Networks

Indoor wireless networks for internet connectivity are typically based on the IEEE 802.11 Wi-Fi standards for the 2.4 GHz and 5 GHz bands, whilst IEEE802.11ad (60 GHz) is gaining in popularity, with gigabit data rates. It might be imagined that this is the ideal communications medium for all networking indoors, but there are other options. IEEE802.11 transceivers are

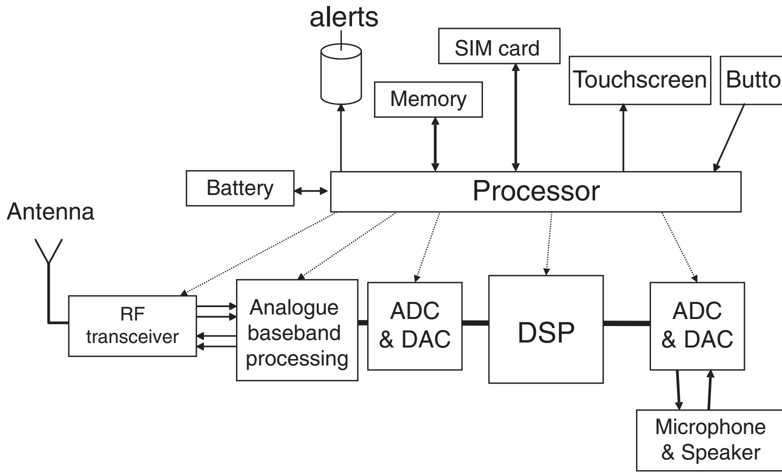

Figure 1.16 A simplified block diagram of a mobile phone.

quite sophisticated and transmit rather high RF power because they are designed to operate at ~10 Mb s^{-1} and above. Devices such as smoke alarms and dimmer switches simply do not require a 10 Mb s^{-1} data rate, and using 802.11 transceivers in them yields a solution that is too expensive and uses more DC power than is necessary. Since many of these devices are battery-powered, this is a major drawback. Hence, there are other radio standards, as well as Li-Fi visible light communication with LED lighting. In many countries, frequencies in the UHF band are allocated for short-range telemetry links; for example, the Rako® wireless control system (as illustrated in Figure 1.17) is available for the 433 MHz band that is allocated in the UK.

The ZigBee® specification is strongly supported by an alliance of companies and has been widely adopted. The ZigBee specification adds additional network, security and application layers on top of the IEEE 802.15.4 radio standard. IEEE 802.15.4 allows operation in unlicensed bands worldwide at 2.4 GHz, at 915 MHz in America and 868 MHz in Europe. It is a low data rate, low-power standard giving a data rate of up to 250 kb s^{-1} in the 2.4 GHz band. A significant advantage of ZigBee is that networks can have very large numbers of nodes; it uses a mesh network topology and nodes may remain dormant for long times using very low DC power. Since a completely wireless, battery-powered product can be installed extremely easily and at low or zero cost, this type of networking is highly attractive as most consumer products retail through the DIY market for retro-fitting (e.g., Wi-Fi itself, which would not have succeeded so well if home users had to pay for a professional installation service). Some of the products that use ZigBee or similar systems include:

- Security systems; motion detectors, pressure pads, cameras, etc.
- HVAC (Heating, Ventilation, Air Conditioning) controls.
- Lighting controls and room-occupancy sensors.
- Curtain and blind motorised controls.
- Utility meter readers.
- Garden watering.

Figure 1.17 Rako® wireless control products using the 433 MHz band. Left: Controls and app. Right: A motorised curtain/blind unit. Images © 2016 Rako Controls Ltd., used with permission.

- Pet feeding systems.
- Entertainment systems.
- Internet-enabled products; e.g., a smart refrigerator.
- Health-monitoring devices.

1.4.6 Hybrid Fibre-Radio Systems

As wireless systems grow in capacity due to increased data rates and higher density of users, it can become very expensive to realise a network that interconnects cells using the raw digital data streams across an optical network. The remote units require Gb per second optical-electrical conversion, followed by DACs, ADCs and up/down frequency translation to convert the digital data to/from modulated microwave or millimetre-wave signals. The result can be expensive radio equipment with significant complexity and DC power. As cell sizes are reduced to increase capacity, this becomes less and less acceptable. A hybrid fibre-radio (or radio-over-fibre) system addresses this problem by transmitting radio signals over the fibre rather than digital data, either at an intermediate frequency or directly at the transmission frequency. This relies on the fibre being a very low-loss conduit for analogue signals modulated onto the optical carrier(s). The remote station can be simplified considerably; for example, the main functional component of the transmitter can simply be an optical-electrical converter (e.g., a broadband photodetector) to extract the desired RF carrier from the optical signal and connect it to the antenna. This type of antenna remoting is already a feature of some sophisticated electronically steered antennas for radar, where there is an advantage in minimising the mass of the antenna array and reducing the spacing between antenna elements by placing the beamforming systems remotely. It has been proposed that this type of remote beamforming be used in basestations for 5G+ millimetre-wave communications. It should be remembered, however, that while the fibre itself is extremely low-loss, the electrical-optical and optical-electrical converters have significant conversion loss. Fibre-radio systems have been very successfully applied already to a wide range of wireless systems, such as in-building distributed antenna systems. The fibre-radio approach is especially relevant where the aim is to improve the indoor reception of cellular, GPS and other signals from outdoors; the fibre can be used as a passive low-loss conduit to indoor repeaters.

1.4.7 RFID, NFC and ICT

Radiofrequency identification (RFID), near-field communications (NFC) and inductively coupled telemetry (ICT) are a related set of contactless systems where the primary aim is to achieve short-range, low-data rate wireless communication for the transfer of basic information. In RFID, a reader communicates with a very simple transponder that can be embedded into a wide variety of objects and relays a unique ID code. NFC can be similar, with a tag inside a poster giving a web link to a phone, for example, but also allows two-way communication, so that two phones could perhaps exchange contact details. Inductively coupled telemetry refers to the situation where the 'tag' includes one or more sensors, such as temperature or pressure, and measured parameters can be relayed back to the reader. These technologies, covered by a wide range of standards, are rapidly being applied to more and more applications and are an important facet of the internet of things (IoT). As a result of the development of miniature integrated circuit transponders, everything can become 'smart'. For example, in the home the washing machine could read the wash labels on clothes, while the refrigerator could monitor food stocks and 'use by' dates and place orders on the internet. In this way, a huge variety of businesses is being transformed, from retail management through to medicine.

Radiofrequency identification is by no means a new idea – transponders have been used on aircraft since World War II as a means of identification for radar systems. However, the development of miniature integrated circuit transponders has advanced so much that it is now technically feasible (if not always economically so) to replace the ubiquitous bar code with an RFID transponder – making it possible to scan a supermarket trolley full of goods automatically as one passes the checkout [10]. The basic idea of RFID (as illustrated in Figure 1.18) is that a tag holds a unique code, and a reader device can determine the code by electromagnetic coupling or transmission of a radio signal to and from the tag. This technology is rapidly combining with smart card and smart label technology to provide a whole new range of possibilities for automation in manufacturing, retailing, transport and security. These new applications are having a profound effect on our everyday lives. Some of the key applications of this technology are listed in Table 1.2. The organisation GS1 [11] sets the standards for identification codes, including optical barcodes, so that they can be understood globally. A number of important RFID standards have been agreed, such as the Electronic Product Code (EPC) Gen 2 standard in the UHF band (860–960 MHz), which is in widespread use.

The simplest and most widespread form of tagging is electronic article surveillance (EAS). In this application, basic security tags are used to set off an alarm when theft is attempted. The tag can be a sticker, embedded metal strip, or a more bulky removable plastic-encapsulated device. These might be thought of as 'one bit' tags. The introduction of 'intelligent tags' which can store information about an item would dramatically increase the number of applications possible, however.

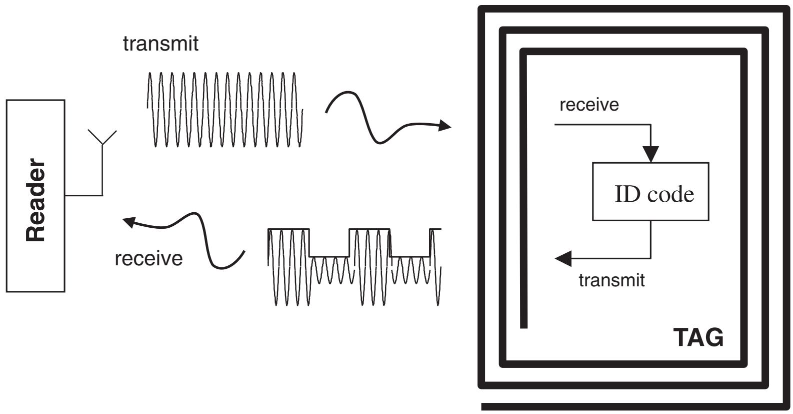

Figure 1.18 A simplified representation of RFID using backscatter modulation.

1.4.7.1 Active and Passive Transponder Tags

There are many types of tag, though not everyone agrees on how they should be classified. The most important types encountered are:

1. Radio tags with a battery or other on-board power source.
2. Radio tags that employ transistor circuits but have no battery or on-board power source, and draw their power from the electromagnetic field of the reader.
3. Completely passive tags; the tag contains no active circuits, and the identity is defined by some geometrical or material structure.

The most widely accepted terminology in RFID is to refer to type 1 as active tags, and type 2 as passive tags since they have no on-board power. Various forms of type 3 tags have been reported, often referred to as chipless RFID [12]. Active tags have the longest read range, but require batteries, solar power or some form of local energy harvesting. The additional DC

Table 1.2 Some applications of radiofrequency identification.

Entry cards	Travel passes
Ski passes	Document identification
Electronic keys	Animal identification
Sports timing	Automotive tolling
Contactless payment cards	Electronic article surveillance (EAS)
Vehicle security	Postal systems – smart stamps
Baggage handling	Laundry
Libraries	Stock control
Offender tagging	Smart coins and tokens
Intelligent appliances	Factory automation
Freight control	Medical records
Post-natal ward security	Asset tagging
Wildlife conservation	Golf ball identification

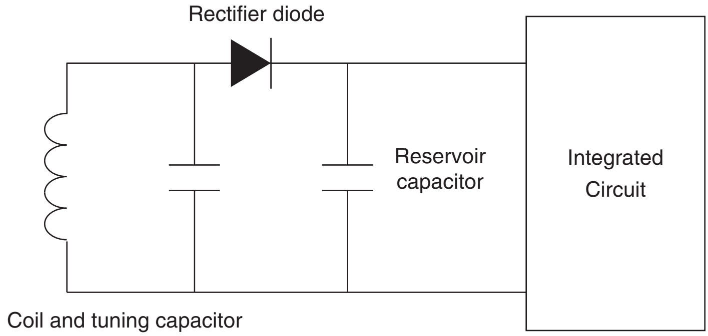

Figure 1.19 A passive RFID tag block diagram.

power makes it possible to transmit much further – examples include the keyfobs of many car alarms and other security and access control systems. Battery life can be as long as 10 years but there is obviously a range/battery life trade-off.

When a passive tag is in the field of the reader antenna, the tag draws power from the field and powers up the chip, as shown in Figure 1.19. If the tag is in the near field of the reader antenna (e.g., inductive coupling in the 125 kHz band) a process of load modulation is generally used for data transfer: the reader can sense the changing load on its antenna. When the tag is further away than approximately one wavelength, it is in the far-field and the data transfer is achieved by means of backscatter modulation, as illustrated in Figure 1.18. With suitable protocols, the data can be transmitted back in such a way as to avoid collision between multiple tags within the reading zone. Since the integrated circuit in a passive RFID tag is powered by the RF field itself, this inevitably limits the read range to 1 m or so in most cases. The biggest application of passive RFID tags is in 'smart cards', and as a result the term 'vicinity card' or 'contactless ID' is often used. This represents an important convergence of technologies and terminologies between tagging and smart cards.

A number of truly passive tags have been developed including electronically readable inks, RF barcodes and SAW devices. The RF barcode, for example, relies on a number of RF resonator strips that have separate resonant frequencies [13]. The SAW devices rely on the much lower speed of propagation of acoustic waves to create a simple geometrically defined transponder that can send back a series of pulses when interrogated by the reader. The pulses are entirely defined by the layout of electrodes on the SAW device; no transistors are required at all.

1.4.7.2 Tags with Position Information

The usefulness of the tag is dramatically increased when the tag is integrated with a satellite positioning receiver, or it can use local Bluetooth/Wi-Fi/cellular signals to deduce its position. The tag is then able to determine its own position and transmit it back to a central location. If, in addition, the tag can connect wirelessly to the internet then there is almost no restriction on the tag location. This combined technology enables freight, vehicles and personnel to be tracked almost without limit. One of the fantasy proposed applications is that if every document in an office had a suitable tag, you would be able to find every document easily with

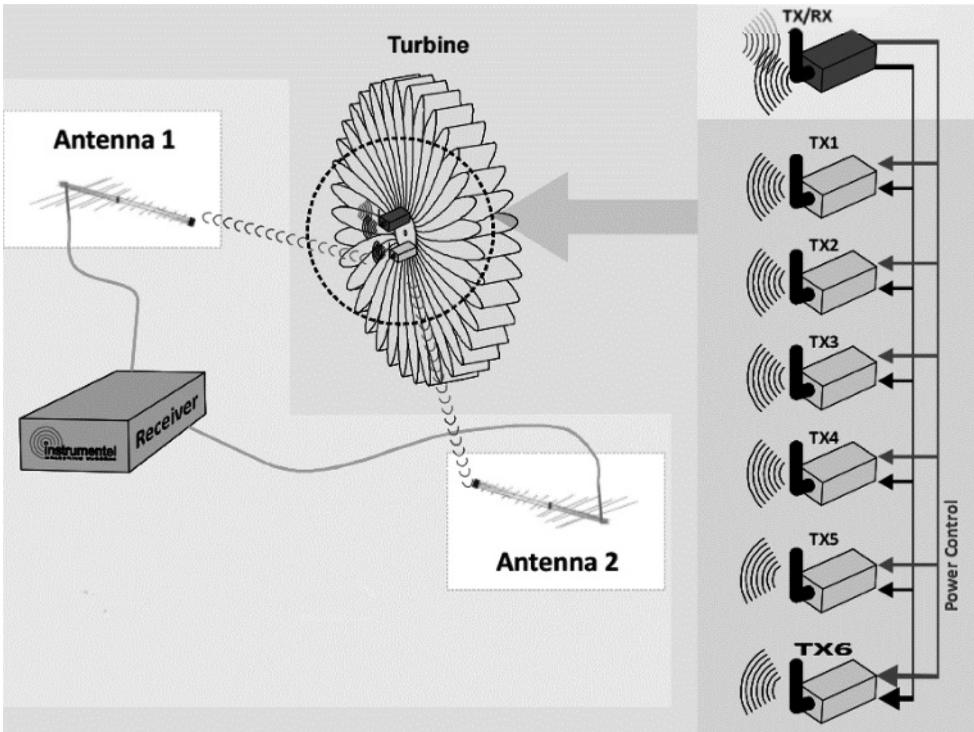

Figure 1.20 Instrumentel^{TM} wireless telemetry system for gas turbine diagnostics. Illustration © Instrumentel Ltd. Used with permission; all rights reserved.

a reader, searching on the reader for the title, keywords, date, and so on, and the document then identifying itself and its location.

1.4.7.3 Inductively Coupled Telemetry

With inductively coupled telemetry, the key additional capability of the tag is the inclusion of sensors, so that parameters such as temperature, pressure or strain can be relayed wirelessly. A battery-less transponder can be made very small and robust, which means it can be embedded in a harsh environment and powered up and interrogated wirelessly through inductive coupling. Instrumentel has been a pioneer of this field [14], and has successfully demonstrated sensors embedded into the pistons and valves of a racing car engine. Figure 1.20 shows a diagram of Instrumentel's gas turbine wireless telemetry system, with sensors embedded in the blades for health monitoring and diagnostics during operation at 100 000 rpm.

1.4.8 Wireless Sensor Networks

A wireless sensor network (WSN) comprises an array of sensing nodes, each of which measures a range of parameter(s) – such as temperature, pressure, sound, vibration, chemical composition, or movement – at its individual location. The node then transmits the data back wirelessly to a central processor at regular intervals. The central processor then collates all the data from the network of nodes and builds up a full picture of the area being monitored. WSNs are a particularly powerful technology when the individual nodes can determine their own position and can form the wireless network autonomously, with no expert set-up. WSNs have many applications, including security and defence, process engineering, environmental monitoring, seismic detection, space exploration, inventory tracking, medicine and smart buildings. The sensor nodes range in size from the smart dust concept to substantial pieces of hardware. The fundamental advantage is the ease of deployment, with particularly important advantages in harsh environments. In process engineering, the low cost of installation means that nodes can be liberally spread around the chemical plant to measure temperature, pressure and vibration. The WSN can then monitor the health of the plant much more effectively than any routine inspection programme, leading to increased safety. In smart buildings, WSNs can monitor the movement of people and reduce energy usage by optimising the HVAC (heating, ventilation and air conditioning) control. Public spaces can be embedded with nodes that sense weapons and explosives, for combating crime and terrorism unobtrusively. In environmental monitoring, WSNs can be rapidly deployed in remote or harsh environments – such as volcanoes, forest fires and inaccessible areas – and used to monitor the situation remotely. In the home, a WSN could monitor the movement and well-being of elderly or other occupants that might occasionally need assistance.

1.4.9 Wearables and Body Area Networks

Wearable electronics has been studied by many research teams and design centres. Wearable electronic products can vary from a smart bracelet to a full body suit. Mobile phones, MP3 players and cameras have been integrated into jackets and Bluetooth used to create a personal area network. There is some fascinating research on the technology of embedding electronics into clothing, including conducting threads, body area communications, and printed or plastic electronics. In the home environment, an important application of wearables is in the unobtrusive monitoring of the wearer's well-being: parameters such as blood pressure, heart rate and temperature can all be measured and the information relayed back wirelessly to the Cloud. A further step is to incorporate therapeutic functions into the clothing, such as massage and vibration functions to relieve pain.

1.4.10 Machine-to-Machine and Robotic Communications

This is a much less-developed application area for microwave and millimetre-wave systems, and yet one that offers many new opportunities. Machine-to-machine (m2m) communications includes both wired and wireless connectivity. One of the key aims is to have equipment, machines of all types, robots and autonomous systems connected to the Cloud. This represents a huge step-change in the number of internet-connected devices, leading the industry to move to IPv6 addressing as the current IPv4 reaches maximum capacity. The range of sectors that will benefit from this machine connectivity is so extensive that it is not possible to do the subject justice in this introduction. One exemplar is the factory of the future, sometimes referred to as Industry 4.0, in which manufacturing systems, RFID-tagged parts and sub-assemblies and robotic assistants all work seamlessly together with human operators. Transport will surely be transformed by connected vehicles, communicating with each other and with smart infrastructure in cities to dramatically reduce congestion, leading to a better quality of life and reduced environmental impact. In healthcare, there is a growing revolution in rehabilitation and surgical robotics, and already studies on networked medical devices and surgical tools have been reported. In security and defence, intelligence is always key to national security, and robotic systems have a tremendous capability to gather data while keeping people out of harm's way. There are, of course, many ethical issues to be debated in that space: Is a robotic mosquito that can sample DNA and administer poison a good idea? And what about a network of autonomous drones with weapons capability? Science fiction has provided many stories about how such technologies can go wrong, but on the other hand we have a very real need to defend ourselves and not put lives at risk.

Connecting machines and robots wirelessly to the Cloud has tremendous potential for providing new capability. For example, currently, a mobile robot needs to carry around its own processing power, and with batteries the amount of computing power that the robot can have is limited. If, instead, the robot is connected to the Cloud wirelessly, then it can use remote processing power to greatly increase its apparent intelligence and give it access to vast databases of information. Clearly, very high data rate communications with low latency are required to make this vision of Cloud Robotics [15, 16] become a reality. From the wireless communications perspective, some of the other challenges for engineers include developing improved techniques for wireless sensor networks, precision localisation techniques, system-in-package technology, microelectromechanical systems (MEMS), high-frequency sensing and imaging, wireless communications networks, MIMO systems, wireless power transfer and energy-harvesting systems. This application sector is therefore predicted to be one that offers RF engineers excellent new career opportunities.

1.5 Conclusion

This introduction has sought to provide a background to microwave and millimetre-wave wireless communications systems by describing some of the main applications and giving some insight into the nature of the industry. Actually, this has included only a very small subset of modern wireless communications systems, focusing on the best-known examples. Today, there is a vast range of other radio communications in use, often for more specialist applications. One of the most recent and impressive demonstrations of the importance of microwave communications was the successful transmission of pictures of Pluto by the New Horizons spacecraft, which used a modest 20 W X-band transmitter to relay data three billion miles back to Earth at a data rate of approximately 1 kb s^{-1}. The best way to fully appreciate the huge variety of applications of the radio spectrum is to study the frequency allocations via the sources already given. Even when focusing only on 5G+ mobile networks, it can be seen that engineers have the ambition to truly change the world by enabling very significant advances in application areas such as mobile health, intelligent transport, future cities and smart grid systems. The prospects for improving lives and creating a more sustainable planet are tremendously exciting, and this is just one of the industry sectors underpinning the IEEE tagline: *Advancing Technology for Humanity*.

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