CHAPTER 1

INTRODUCTION TO MICROWAVE LOS LINK SYSTEMS

1.1 INTRODUCTION

From a generic standpoint, a telecommunication network enables the exchange of information among users or devices that can be either fixed or mobile. This general view contains the first simple classification of telecommunication networks into fixed and mobile. Independently of the mobile or fixed nature of the target devices, the signals involved in the communication process transport digitized information that is associated with final services such as voice, pictures, video, or general data.

Every network is composed of two basic components: network nodes and transmission systems. The network nodes provide the control, access, aggregation/multiplexation, switching, signaling, and routing functions. The transmission systems enable the transport of signals either from the user devices to the network nodes or between different nodes of the network. The transmission systems can be based on different delivery media. Usually, the transmission media have been divided into wireless systems, where the information is delivered by means of electromagnetic waves that propagate through the atmosphere, and systems based on transmission lines, where the electric or optical signals propagate through a closed medium. The metallic transmission of electric signals uses lines that usually are copper pairs or coaxial cables, whereas the optical signals are sent over glass fiber cables.

Transmission systems can be found in any of the two subnetworks that compose a generic telecommunications network: access network and transit network. The

Microwave Line of Sight Link Engineering, First Edition. Pablo Angueira and Juan Antonio Romo.

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access network enables the communication between the network and the user devices, whereas the transit network provides all the required functions that interconnect different access sections, including network control, signaling management, switching, interfacing with other networks, etc.

In this network context, a radio link of the fixed service (FS) [as per Radiocommunication Sector of the International Telecommunication Union (ITU-R) terminology)] is any radiocommunications link between two fixed stations based on the propagation of signals through the atmosphere at frequencies higher than 30 MHz. Currently, there is a tendency to use more the generic term of fixed wireless system (FWS), which is used to identify the telecommunication systems operated for FSs and that are used in access and transport application scenarios. Those systems are conveyed by electromagnetic wave propagation, in any form, with a limit that has been set in 3000 GHz. Terrestrial point-to-multipoint systems, terrestrial point-to-point systems, high-frequency (HF) systems, high-altitude platform systems (HAPS), and even free space optic links fall into the FWS category.

Microwave line-of-sight (LOS) links covered by this book are a subgroup of the FS or FWS general classifications. Microwave LOS links are composed of point-to-point systems between two terrestrial stations that transmit and receive signals taking advantage of the propagation of waves through the lower part of the atmosphere (troposphere). Microwave links operate in LOS condition in frequencies from 400 MHz to 95 GHz under specified availability and quality conditions. These systems are in practice referred as microwave links (MW links), LOS microwave, fixed service radio links, or simply radio links.

The frequency limits mentioned earlier are associated with the frequency band assignments that international regulatory bodies have reserved for fixed service links. Currently, a majority of the systems operate in frequency bands between 4 and 40 GHz. Higher frequency bands are used in links where the path between stations is rather short (usually less than 1 km and, in any case, no longer than a few kilometers due to availability constraints associated with rain attenuation).

A basic point-to-point microwave LOS link is composed of two nodal stations, each one at the edge of the link path, without obstacles in the propagation path that could cause blocking or diffraction, and that use antennas with high directivity, also named narrow-beam antennas.

Microwave LOS links are designed to preserve the LOS propagation path as the main propagation mechanism. This condition implies that the direct component of the space wave is well above the terrain irregularities and any diffraction effects are considered negligible under standard conditions. In practice, the LOS component coexists with additional propagation modes such as the reflection on the surface of the earth, diffraction in obstacles due to anomalous refractive conditions and multipath propagation originated both on the surface of the earth and on higher layers of the troposphere. In the design process of a MW link, the availability of accurate terrain maps, which also contain any man-made construction candidate to create diffraction, is a key requirement. Figure 1.1 shows a simplified model of the possible propagation modes in a point-to-point link.

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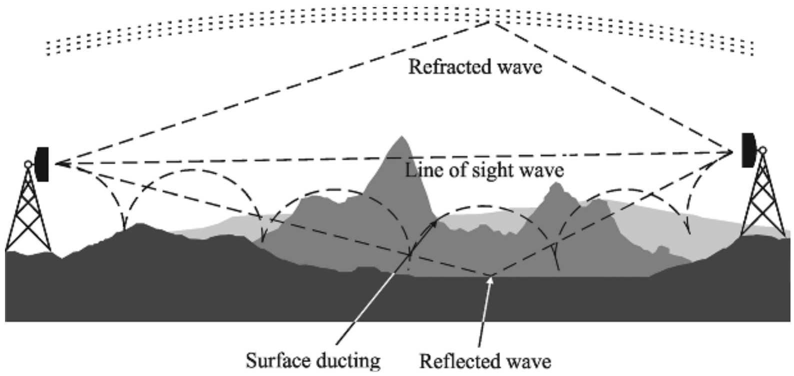

FIGURE 1.1 Propagation modes in a microwave LOS link.

In the likely event that path distance between the locations that will be communicated exceeds the LOS distance, due to terrain irregularities or simply due to the curvature of the earth, the link will be divided into concatenated shorter sections (called “hops”) that are created by means of including repeater stations.

In most cases, microwave LOS links are bidirectional systems, with full duplex capacity provided by frequency division multiplex schemes. The simplest example would require two carriers, each one aimed at transporting the information in one direction. An assignment of two frequencies, each one for each direction of the communications, is called radio channel. Sometimes, LOS links can be simplex systems, transporting information in only one direction. An example of this application can be found in the transport section of terrestrial broadcast systems, where the video, audio, and data are conveyed from a production or aggregation center to the broadcast stations that will later broadcast the contents to the end users.

This chapter provides an overall view of the microwave LOS links, describing the specific terminology that will be used in this book, the most relevant characteristics of the technologies involved and identifying the most widespread application fields of microwave LOS links. The chapter contains the basic principles of the planning and design process of a microwave LOS link, starting from the definition of a link budget and identifying the main signal degradation sources that influence the fulfillment of the quality requirements of the link. The perturbation sources considered will be related to propagation through the troposphere, noise sources, and interferences. After the introductory picture given in this chapter, each one of the design procedures and modules will be covered in detail in later chapters.

1.2 HISTORIC EVOLUTION OF RADIO LINKS

The first experimental microwave LOS link was designed and installed by the Bell Labs in 1947. The system was intended to provide a two-way communication between two stations in New York and Boston. The link was an analog system in the 4 GHz

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band that used frequency modulation and frequency division multiplex techniques. The equipment was based on vacuum tubes. The evolution of this system led to further developments in the United States, Australia, Canada, France, Italy, and Japan during the 1950s. The preferred bands during this period were 4 and 6 GHz. In this context, in 1960, the National Long Haul Network was designed to connect the East and West Coasts of the United States of America, with a total length of 6500 km and about 125 active repeater stations.

In 1968, the first digital microwave LOS link was installed in Japan. This first digital system operated in the 2 GHz band, using phase shift keying (PSK) modulation with an equivalent capacity of 240 telephone channels. After this first digital landmark, the rollout of digital microwave relay systems starts in the 1970s and continues over the 1980s. During this period, analog systems did not disappear and coexisted with the new digital links. During the 1980s, the analog systems started being progressively replaced by equivalent digital systems, process that was generally completed by the first years of the twenty-first century.

The use of multilevel modulation schemes in high-capacity links was spread out during the first years of the 1980s. These systems were based on plesiochronous digital hierarchy (PDH) transport techniques. The inclusion of adaptive equalizers and diversity reception schemes to fight fast fading associated with multipath propagation components are also relevant milestones of the mentioned decade.

During the 1990s, the most relevant advances over the state of the art are a consequence of the new fields of application for microwave LOS links. Although the typical use for long-haul transport links in telephone networks started to decline in favor of fiber-optic links, the use of microwave LOS in access networks grows significantly, both as transport infrastructure for cellular mobile access networks and also as supporting infrastructure in fixed access networks. The exponentially growing access networks of the 1990s require new frequency bands and enhanced efficiency in bits per hertz. During the 1990s, synchronous digital hierarchy (SDH) and asynchronous transfer mode (ATM) technologies were widely adopted by transport networks, including those based on microwave LOS links.

During the first decade of the twenty-first century, there has been a convergence between mobile and fixed services and a progressive implementation of Internet protocol (IP) packet switching (PS) traffic in all networks, both in the access and transit network sections. Microwave LOS links have not been immune to this tendency and a progressive adaptation to this scenario has been put in place. The first versions consisted of interface adaptations for the coexistence of Ethernet and PDH/SDH traffics in the same links that later evolved to all IP systems. Currently, Ethernet radio equipment provides a significant flexibility to adapt the bandwidth assignments to different services carried by the MW link system. Maximum throughput values today range from several hundreds of megabits per second to a few gigabits per second if latest optimization techniques are used (dual polarized channels, high-order modulations, multiple in multiple out, etc.).

The target of new technology developments during the last years has evolved to a progressive enhancement of the spectral efficiency, following the same tendency of increasing bandwidth demands of broadband multimedia services. Nowadays, the effort focuses on increasing the capacity while maintaining performance (availability and quality), as well as a better exploitation of spectrum resources in dense frequency reuse scenarios. Following chapters will cover some of these techniques, such as adaptive modulation techniques with high-order schemes (i.e., 512 - 1024-QAM), frequency reuse channel arrangements with dual polarization or high-performance antennas.

1.3 POINT-TO-POINT FIXED COMMUNICATION TECHNOLOGIES

In order to set up a communication connection between two locations, there are several technical choices, the microwave LOS link being just one of the possible options. Among the alternatives, there is a set of choices that involve physical carriers: systems over copper pair cables, links using coaxial cables, and fiber-optic cable links. Additional alternatives are based on radiocommunication systems such as satellite links, other terrestrial point-to-point systems (i.e., transhorizon links), HF fixed systems, communication links using HAPS, free space optic (FSO) links, and point-to-multipoint wireless communication systems.

The choice of the transmission media is one of the first actions that a communications engineer must take, always at the first stages of the design of a communication system. This section will describe briefly the different choices for establishing a link between two locations, and the different advantages and drawbacks of each alternative will be discussed, always with the microwave LOS link as the comparison reference.

From a general standpoint, terrestrial microwave LOS links have inherent advantages that are a consequence of wireless propagation without the need of having a physical carrier that connects transmitter and receiver. This advantage is notorious in areas with irregular orography, zones where deploying a cable system is difficult, areas where physical access is a challenge, and cases where common infrastructures are not developed.

The microwave LOS links are usually the solutions with lowest cost in the case of access and transit network if the network rollout requires fast and flexible connection deployments in dense network scenarios, such as wireless mobile systems. The possibility of transporting physically the equipment of a microwave LOS link provides further benefits for its use in the case of emergency situations, natural disasters, or temporary backup system in severe damages suffered by fiber-optic link cables.

The major disadvantage of microwave LOS links is associated with the restriction imposed by the LOS requirements of these systems. In dense urban environments, blockage from buildings is a problem to set up links with the minimum number of hops possible. In cellular access networks, the intense reuse of frequencies provokes interference problems that require complex and careful design procedures. Moreover, the need of periodic maintenance actions in towers and stations with difficult access is one of the remarkable disadvantages of these systems. Finally, the complete dependency of the system performance upon the unstable mechanism of propagation through the troposphere is a challenge for the radiocommunications system design engineer.

1.3.1 Cabled Transport Systems

1.3.1.1 xDSL Technologies Historically, copper cable pairs have been massively used as the physical carrier in the local loop, from the telephone office to the customer premises, as well as the physical means to transport analog and digital multichannel links between offices. As a consequence, the telephone companies, most of which have become today's global telecom operators, have a wide outdoor plant infrastructure based on copper pairs.

In the case of point-to-point applications, today, there are commercial solutions that multiplex different flows and sources (PDH, Ethernet, etc.) into a single flow in a link over copper pairs (two and four wires depending on the system). These links can use some of the variations of a family of technologies called digital subscriber line (DSL), that in addition to be last mile applications, can be used as the lower layer technologies for transport systems over copper pairs. Figure 1.2 shows a block diagram with an example of DSL links.

The DSL family is a group of standards that offer different alternatives mainly targeting access networks over the copper outdoor plant. There is a variety of alternatives depending on the specific requirements as symmetry/asymmetry of the upload and download channels, maximum throughput per maximum local loop length, etc. Among the variations, asymmetric digital subscriber line (ADSL), high data rate digital subscriber line (HDSL), symmetric digital subscriber line (SDSL), single-pair high-speed digital subscriber line (SHDSL)/HDSL 2, very high speed digital subscriber line (VDSL), and VDSL2 are worth mentioning. Figure 1.3 shows a comparison among these technologies differentiating the symmetrical/asymmetrical nature of the standards as well as the maximum link length versus achievable bit rates.

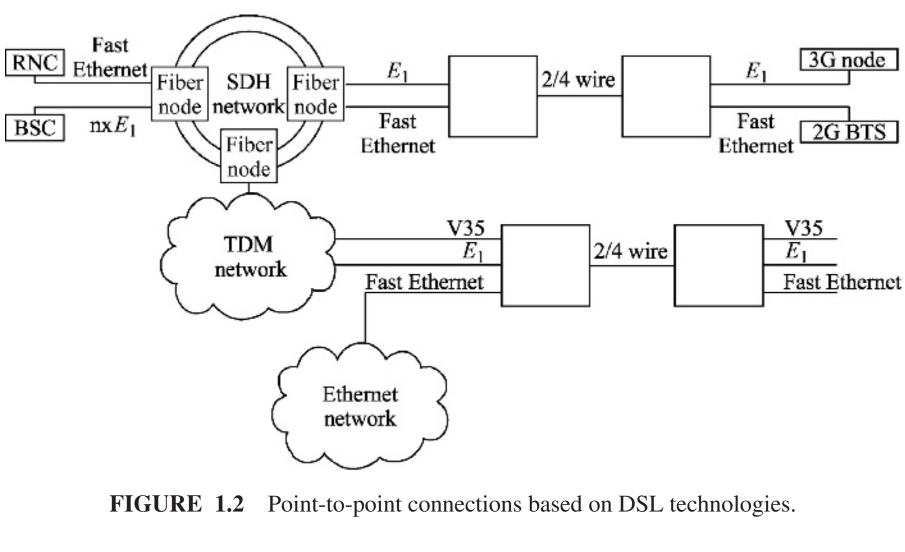

FIGURE 1.2 Point-to-point connections based on DSL technologies.

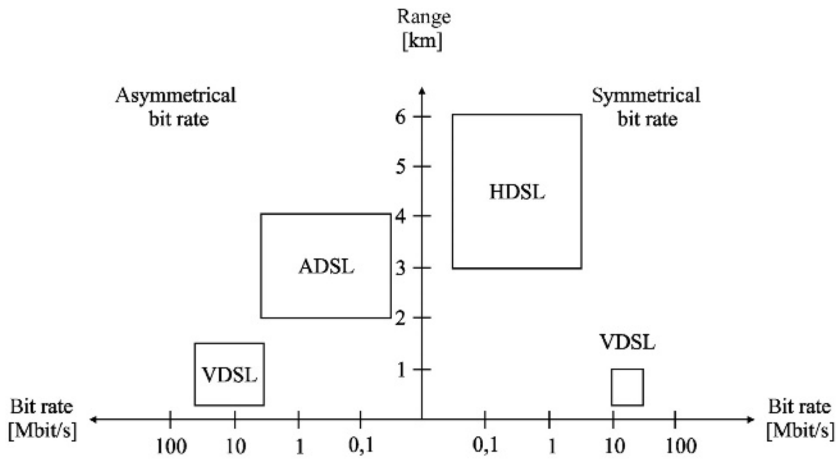

FIGURE 1.3 xDSL technologies. ADSL, asymmetric digital subscriber line; HDSL, high data rate digital subscriber line; VDSL, very high-speed digital subscriber line.

In comparison with microwave LOS links, DSL technologies are used today extensively in access networks for connecting consumer premises to the transit network (Figure 1.4). The success of DSL standards in access networks has been based on their flexibility and capacity for fast and inexpensive deployments over the existing copper outdoor plant, and, at the same time, providing bitrates high enough for wideband internet access, video distribution and in general access to networked multimedia contents. The most remarkable limitation of these systems is usually a maximum bitrate/distance limit caused by link density in urban areas and by the difficulties of propagation through the copper pair carrier. The propagation channel over copper pairs involves a considerable list of relevant impairments (interferences, crosstalk, attenuation, impulse noise, etc.). The problems in these networks are in many cases amplified by the fact that the outdoor plant is rather old.

1.3.1.2 Fiber-Optic Links Fiber optics has a long list of advantages for point-to-point link applications. Fiber-optic links have extremely high bandwidths, very low attenuation values that enable long links without repeaters and transmission quality specifications that are almost unaffected by environmental changes. Additionally, these features remain stable over time. Fibers are grouped in variable number in fiber-optic cables that have special isolation, reinforcement, and protection elements in order to preserve the integrity of the fibers. Each fiber can convey a few gigabits per second per wavelength. If wavelength division multiplex or dense wavelength division multiplex techniques are used with a cable that contains multiple fibers, for practical purposes, the transport capacity of these links is unlimited, and the network bandwidth is limited by other functions such as switching or interfacing with other networks.

Fiber-optic cables present disadvantages that are a consequence of the need for special arrangements in laying the cable. In most cases, especially in urban areas,

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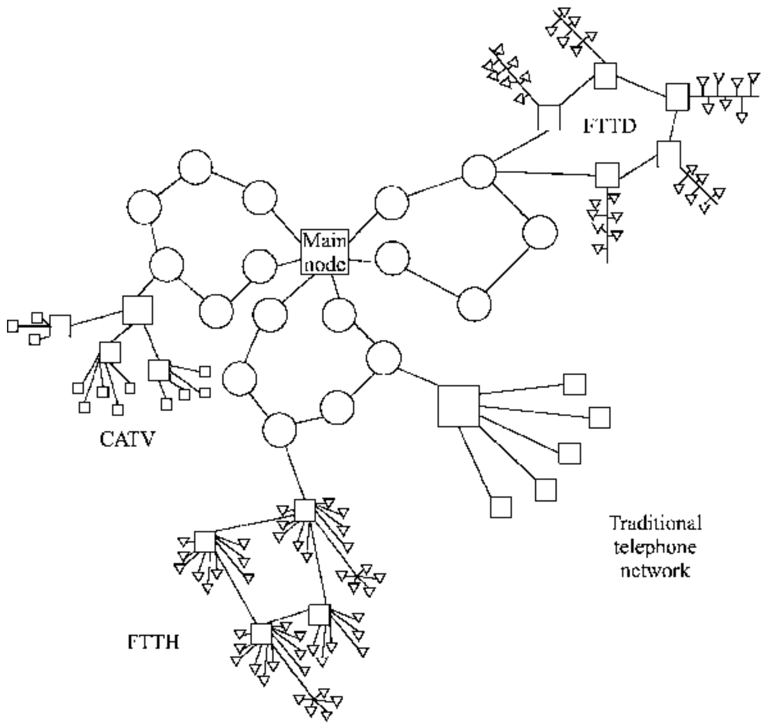

FIGURE 1.4 Network diagram showing different subnetworks (access and transit) based on fiber-optic cables.

fibers are laid in underground ducts and subducts, where special polyvinyl chloride pipes are installed previously. The construction of this underground concrete infrastructure in urban areas is expensive and time consuming, and it increases significantly the number of administrative permits required in the network deployment process. Moreover, in areas with irregular terrain, laying a fiber-optic cable is difficult and very expensive.

Fiber-optic systems can be found today in all the sections of a telecommunications network, including terrestrial long distance links, international submarine high-capacity links, high-capacity intercity and metro ring transport systems, and not forgetting the increasing number of high-speed access networks based on fiber-optic cables. Figure 1.4 shows a network diagram example with different sections in a fibre-optic network.

The application in access networks has different approaches depending on the distance between the fiber cable termination and the user premises. Figure 1.5 shows the most common schemes known as fiber to the x (FTTx), where x refers to the terminating point of the fiber: fiber to the home (FTTH), fiber to the building (FTTB), fiber to the curb, fiber to the neighborhood (FTTN).

FTTH is based on fiber-optic cables and optical distribution systems for enabling wideband services (voice, television, and Internet access) to residential and business

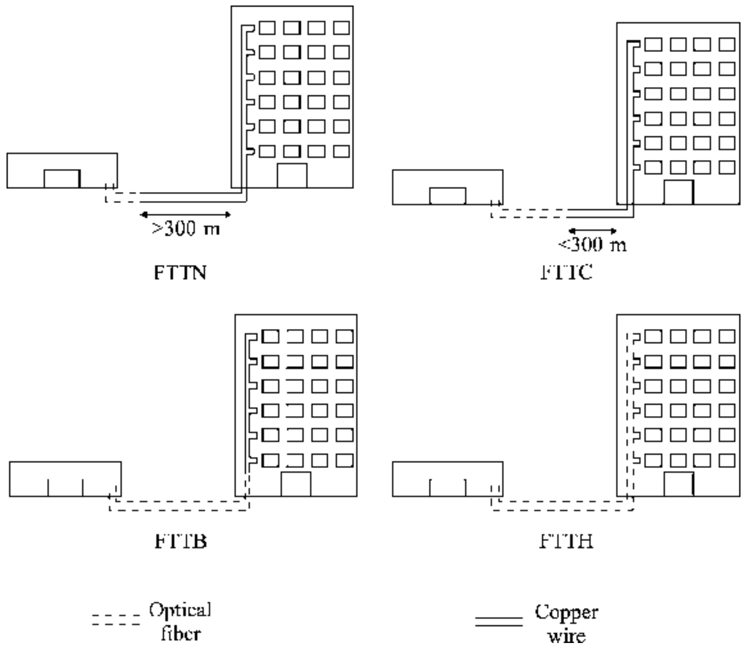

FIGURE 1.5 Fiber to the x (FTTx) technologies. Fiber to the neighborhood (FTTN); fiber to the curb (FTTC); fiber to the building (FTTB); fiber to the home (FTTH).

users. The optical distribution networks are passive optical networks (xPON). Once again there is a list of variations of the passive optical family: asynchronous transfer mode passive optical network, broadband passive optical network, gigabit-capable passive optical network, and gigabit Ethernet passive optical network.

A well-known case of FTTN is hybrid fiber coaxial (HFC) networks. These networks have been widely deployed in residential environments to provide traditional cable television and telephone services that have been complemented today with wideband Internet access. The most widespread open systems interconnection Layer 2 standard in today's HFC networks is DOCSIS (data over cable service interface specification).

1.3.2 Satellite Communication Links

Satellite communication links are a type of radiocommunication system established between two earth stations enabled by an artificial satellite that acts as a repeater station. The fixed satellite service (FSS) is defined by the ITU-R as the point-to-point link between two earth stations. FSS systems are based on satellites located on geostationary orbits. These orbits are geosynchronous. The orbit is on the equatorial plane and the satellite travels along the orbit with an equivalent orbital period, which is approximately the same as the rotation period of the earth. Geostationary satellites are thus fixed for an observer on earth's surface, independently of its latitude–longitude position (Figure 1.6).

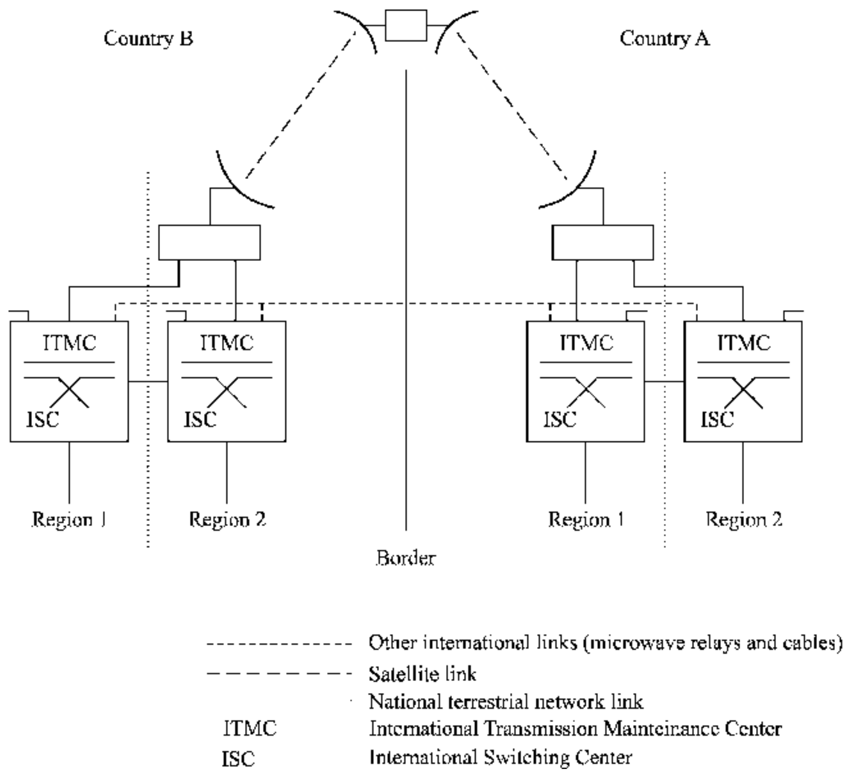

FIGURE 1.6 International connection by a fixed satellite service (FSS) link.

Satellite links have been intensively used in the past two decades as the solution for long distance point-to-point digital telephone channel transport as well as generic data, especially in the context of international communications or in countries where the distances make other solutions less adequate. This application involves earth stations with remarkable bandwidths, high equivalent isotropic radiated power (EIRP) values and Figure of Merit G/T (a parameter that quantifies the station gain vs. overall noise at the receiver, thus specifying sensibility) values also very high. These high-capacity satellite links have been progressively substituted by fiber-optic connections (land and submarine) while the satellite option is in many cases the redundant backup system for ensuring link availability in the event of a fiber link failure.

Satellite links are also adequate for point-to-multipoint networks in remote zones and over wide service areas. A common application is very small aperture terminal (VSAT) networks, where a nodal station dynamically controls the access of a high number of terminals disseminated over the coverage area. The services provided by today's VSAT networks are similar to a generic telecommunication network, providing voice, multimedia, and data network access.

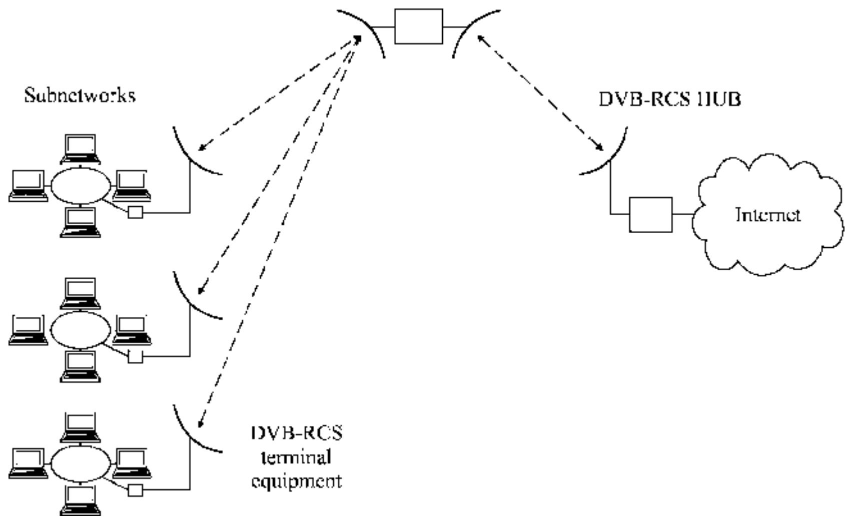

FIGURE 1.7 A very small aperture terminal (VSAT) network architecture based on DVB-RCS (digital video broadcasting-return channel satellite).

Figure 1.7 illustrates the typical architecture of a VSAT network where all the terminals are connected to the central hub through the satellite link. The central hub manages the operation of the VSAT system and acts as the gateway between the VSAT and other networks (Internet).

1.3.3 Other Fixed Wireless Systems

1.3.3.1 Free Space Optic Links FSO links are based on optical transmitters that send a narrow beam optical signal that propagates through the troposphere towards an optical receiver station. The optical nature of the energy involved is associated with the wavelength of the signals propagated (1550 nm, 780–850 nm, and 10 000 nm), in some cases very similar to the ones used by fiber-optic links. The main disadvantage of FSO links is the limited range that can be achieved today, due to propagation impairments. The limiting factor for FSO links is fog. In addition, other perturbation sources might be caused by sunlight, visibility obstructions, rain, snow, etc. Those impairments create scintillation and different degrees of fading. These perturbation sources limit the practical link ranges to 1 km. Figure 1.8 illustrates a simplified scheme of an FSO link intended to interconnect two local area networks of near buildings.

FSO links are a very interesting solution for short distances, which is complementary to microwave LOS links in dense urban environments. The major advantages if compared with LOS links are the wide bandwidths, simple equipment, and absence of interferences, which eliminates the complex frequency coordination studies from the design process.

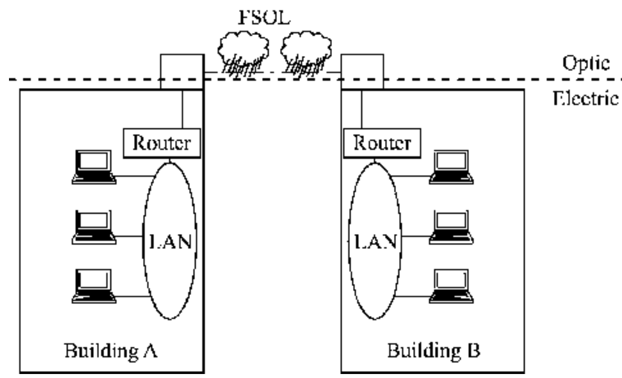

FIGURE 1.8 Free space optic (FSO) link.

1.3.3.2 Wireless Point-to-Multipoint Systems Point-to-multipoint wireless systems enable a communication between a nodal station and different stations spread out within the coverage area. Each nodal station has an associated coverage area, usually up to several tens of kilometers where substations can be installed. The network is usually composed of several nodal stations, and thus, there should be a frequency reuse coordination and interference analysis process when defining the coverage area associated with each one. This process is similar to the planning methods used by mobile cellular networks. These systems are normally used to provide wideband access to data services, both in urban residential and rural environments. The services offered today include both generic data access (Internet) and real-time services such as voice communications or television.

One of the most popular examples of point-to-multipoint systems is wireless metropolitan area networks (MANs), and different standards have been developed worldwide. The Institute of Electric and Electronic Engineers (IEEE) has developed the IEEE 802.16 standard, whereas the European Telecommunications Standards Institute has standardized the HiperACCESS and HiperMAN technologies within the broadband radio access network (BRAN) workgroup.

The radio interface of these standards can be configured for different data transmission throughputs in a variety of frequency bands in the lower part of the spectrum (2–11 GHz) and also in higher frequencies (26–31, 32, 38, and 42 GHz). The systems operating in the higher part of the spectrum are referred as high-density fixed services (HDFS).

Among all the technologies in use today, the local multipoint distribution system (LMDS) is worth mentioning. LMDS uses the frequency bands that range from 26 to 31.3 GHz and from 40.5 to 42.5 GHz. These high frequencies limit the coverage range to 5 km, due to the LOS requirements and deep fading effects associated with hydrometeors. LMDS is specified by the standard IEEE 802.16-2001 for wireless MAN environments. The system has been successfully deployed in Europe, whereas the commercial rollout in other parts of the world (Asia and North America) has not been as immediate as expected due to difficulties in finding available frequencies.

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1.3.3.3 High-Frequency Links The FS systems operating in the frequencies that range from 3 to 30 MHz are an interesting alternative to point-to-point communications in applications where the link distance is very long (hundreds of kilometers) and the traffic capacity requirements are low.

These systems are especially adequate for setting up fast emergency communication systems, in cases of natural disasters that destroy or interrupt the normal operation of standard wireless or wired communication networks. In these disaster relief situations, HF links can be used as the first means to communicate (sometimes broadcast) alarm messages to communication stations or become the basic communication system to coordinate disaster relief operations.

The propagation in these frequencies is very unstable and difficult to predict. The propagation mechanism associated with these bands is the ionosphere wave. This propagation mode is based on transmitting from a station with a certain elevation angle towards the ionosphere, where the signal suffers refraction on the different layers of the ionosphere, and returns to the earth some hundreds of kilometers away from the transmitter. In certain cases, and depending on the antenna system, the frequency and the terrain soil electrical features (propagation over the sea is the most favorable case), the propagation through surface waves is also noticeable.

1.3.3.4 High-Altitude Platform Stations (HAPS) There is a special type of FS links that are based on platforms elevated at high altitudes that in theory enable a communication link between arbitrary locations of the coverage area of the HAPS platform, with high bandwidth capacities, in the same order of magnitude as satellite links. The HAPS "vehicle" is located at an altitude of 21 and 25 km and must be kept in place by complex control systems and some type of propulsion engine. HAPS systems are intended to have a cellular architecture in order to reuse the spectral resources intensively. User terminals are usually divided into three categories: urban area receivers, suburban receivers, and rural area devices.

There are frequency assignments to HAPS systems in the 800 MHz and 5 GHz band, whereas the relevant spectral resources remain at 18–32 and 47–48 GHz.

1.4 FIELD OF APPLICATION AND USE CASES

Microwave LOS link systems have played and still play a fundamental role in long-haul and high-capacity communications systems, both in transmission systems between nodes in telecommunication networks and in transport sections of broadcast networks.

Another classical application of microwave LOS links is the transport (backhaul) in mobile cellular networks, where it has become the dominant transport technology in global markets worldwide. This dominant position will be likely kept in next generation of wideband wireless communication networks.

An increasing interest field is related to access networks for licensed and unlicensed short distance links above 17 GHz, where the equipment is compact and reliable. The MW links are especially adequate for access sections in telecommunication networks, due to their economic advantages and easy deployment in practically any rollout scenario.

Next sections describe the most relevant features of the application scenarios where microwave LOS links are usually exploited.

1.4.1 Backhaul Networks

Traditional transport or backhaul Networks have used microwave LOS links that operate in frequency bands below 15 GHz. The typical hop length of these systems is in the range from 30 to 50 km and the associated bitrate capacity is equivalent to medium-to-high capacities in PDH or SDH systems (usually above 34 Mbps).

As the traffic demand increased, many service providers have deployed fiber networks that have substituted MW links as the leading technology in the mentioned network sections.

Most administrations and carriers, specially in places where the infrastructures are not well developed or in areas where topography is a challenge for deploying telecommunication networks, assume that even an increase of its use is not probable, MW links will still be used for some time in these low-frequency bands, with medium and low throughput capacities.

Some other administrations forecast a decrease in the use of microwave LOS links for high-capacity applications, shifting their field of application towards a role of backup systems that will be complementary to fiber-optic networks. Nevertheless, the same administrations envisage an intense use of microwave LOS technology in point-to-point short-distance applications, where capacity is not a relevant factor, as a means to support the increasing demand of traffic in access networks, especially in rural zones, remote areas, or areas where access is a challenge.

1.4.2 Backhaul in Mobile Networks

Microwave LOS links are the usual communication system for transport functions between base stations (BSs) (or equivalent in 3G and 4G networks), upper level control nodes (i.e., base station controllers (BSCs) in global system for mobile communications) and even with higher order nodes such as mobile switching centers (MSCs) and Packet Switching nodes. When installed in BSs, microwave LOS links share infrastructure and towers with the cellular access network equipment.

During the last two decades, second- and third-generation International Mobile Telephony 2000 networks have been deployed worldwide to serve traffic demands of voice, instantaneous messaging, and e-mail services. These standards are based on BSs furnished with E1 or T1 interface modules. These interfaces can be used directly for 2G TDM (time division multiplex) native traffic transport. In the case of 3G networks, the traffic is encapsulated into ATM and later conveyed by physical PDH/SDH interfaces. In any case, the traditional approach is a TDM link operating in different frequency bands, which are chosen by the operator depending on the link length requirements. Typical frequency allocations for this application can be found in the 10, 11.5, 18, 23, and 38 GHz bands.

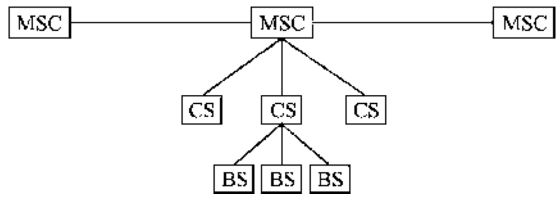

FIGURE 1.9 Interconnection topology for transport links in a mobile network.

Usually, the transport network topology is built upon different hierarchical layers that begin at the access aggregation nodes, following to the control centers (CS) and even to the switching centers (MSC). The latter link type (in MSCs) is only used in those cases where optical fibers are not available for this purpose. The links are in most cases cascaded, using multiple redundant paths, and providing high availability values even in the case of rough propagation conditions or equipment failures. Figure 1.9 illustrates the hierarchical interconnection topology from BSs to MSCs.

The situation described so far is not static. Mobile networks are experimenting a continuous change in technologies in use and also in services and traffic demands and patterns. It is remarkable that the exponential increase of data traffic demands that already deployed 3G networks are experimenting in the first years of the second decade of the twenty-first century.

Wireless access technologies are evolving to mobile wideband data access systems that transport packet mode traffic sources using direct Ethernet interfaces. This evolution has taken place in parallel to the increasing demand of basic data services, streaming, multimedia applications, and real-time mobile television, among others. All these services require higher bandwidths and, at the same time, are more sensitive to network delays. The emerging network technologies that are being used to serve the earlier-mentioned demands are known as wideband mobile systems and some technology examples are high-speed packet access, evolution-data optimized access, long-term evolution (LTE), and worldwide interoperability for microwave access. As a reference value, LTE cells are being designed with a target bitrate of 100 Mbps, with native IP BS Ethernet transport interfaces, that substitute E1/T1 connections.

The transport infrastructure of these new wideband mobile standards will have more restrictive requirements in terms of bandwidth, deployment flexibility, spectrum efficiency, and price. As the access networks evolve to optimized systems with capacities and efficiencies close to the Shannon limit, and all IP operation, the associated transport infrastructure should evolve accordingly. In any case, the capacity increase is not homogeneous over the entire transport infrastructure. Links close to access nodes will have lower capacity increase demands, while systems in higher aggregation levels will require a significant increase on traffic capacity.

The introduction of the IP on the transport section will increase the total capacity of the network at a lower operation cost per capacity unit. The evolution from the TDM traffic environment to the all IP scenario is carried out following an evolutionary approach. The intermediate links will transport a mixture of TDM and Ethernet

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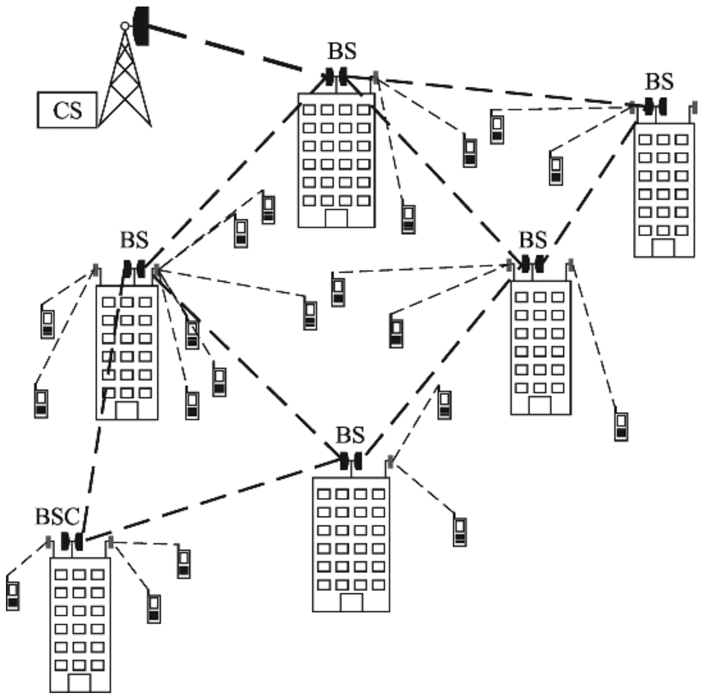

FIGURE 1.10 Microwave LOS links in a cellular mobile access network.

traffics up to the moment where the network is ready for all the IP operation. Another relevant aspect that is being studied is the adaptation of new quality measures and availability criteria, adapted to packet traffic profiles.

A paradigmatic example of the evolution described is Gigabit Ethernet Radio. This technology combines the basic features of Ethernet with high spectral-efficiency techniques that enable link throughputs around several gigabits per second, for microwave LOS links operating in usual frequency bands from 6 to 40 GHz. These high capacities are even increased if wider channeling structures are used in frequency bands around 42, 70, and 80 GHz. Figure 1.10 shows a simplified example of a cellular mobile access network with MW links associated with each access node.

1.4.3 Metro and Edge Networks

Metro networks are transport networks in urban areas based on fiber-optic rings with high capacities and usually based on synchronous optical networking SONET/SDH and Metro Ethernet standards, which transport voice, video, TV, and data traffic flows. The application of microwave LOS link in this scenario is a complementary role under certain specific conditions:

- Short-term alternative solution to fiber-optic links in cases where administrative permits for civil works delay the deployment of the fiber cable.

- Links that enable redundant paths that could reconfigure and carry traffic originally conveyed by the optic fiber ring in the cases of ring disruption. This kind of protection measure is especially relevant for high-capacity hubs, or simply nodes that are more vulnerable to accidents and dual cuts.
- Backbone extension to reach locations outside the limits of urban areas.

The microwave LOS links used in metro networks are usually designed with frequency plans in high bands, due both to the usually short link distance and the commonly high bitrate capacity requirements.

1.4.4 Fixed Access Networks

The connection of customer premises to the wideband fixed access networks is usually carried out either by means of copper pair or fiber-optic systems. This application also includes connections for LAN bridging or remote LAN connections. Microwave LOS links and high-density point-to-multipoint systems are used as alternative or complementary choices depending upon the system deployment costs if copper is not available and in cases where fast system deployment is a requirement.

Microwave LOS links used in this environment are usually high-capacity IP links, in line with the evolution tendency in access networks from ATM to IP. The frequency bands for this application are usually in the upper part of the spectrum, as the frequencies assigned to HDFS: 32, 38, 42, 52, 56, and 65 GHz. In some cases, where these bands might be saturated, links below 15 GHz are also possible. Figure 1.11 shows an example of connections by means of metro and microwave LOS links.

1.4.5 Additional Use Cases

A traditional application of microwave LOS links is the physical support to corporate networks of private companies such as utilities (electricity, gas, etc.), public security, and other industries, which might require to connect buildings and other installation facilities within an area.

Another use is LAN or personal area networks in indoor environments, where radio links are used for high-speed multimedia service connections between local devices in indoor areas, offices, etc. This application usually takes advantage of the highest bands of assigned to FSs, starting at 57 GHz. For example, in the United States, this application uses the 60 GHz band (57–64 GHz), 70 GHz (71–76 GHz), 80 GHz (81–86 GHz), 95 GHz (92–95 GHz).

An additional traditional field where microwave LOS links have been intensively used is temporary portable link installations for special events or for distress operation communications in the case of natural disasters.

Finally, it should be mentioned that microwave LOS links, in addition to their use in licensed bands, can operate in ISM bands (5 GHz), within the subband that ranges from 5.25 to 5.35 GHz and 5.725 to 5.825 GHz. If interferences to and from other services are carefully handled, these frequencies can be used to set up links in rural areas with ranges over 20 km as a means to extend urban access networks to those hypothetically isolated areas.

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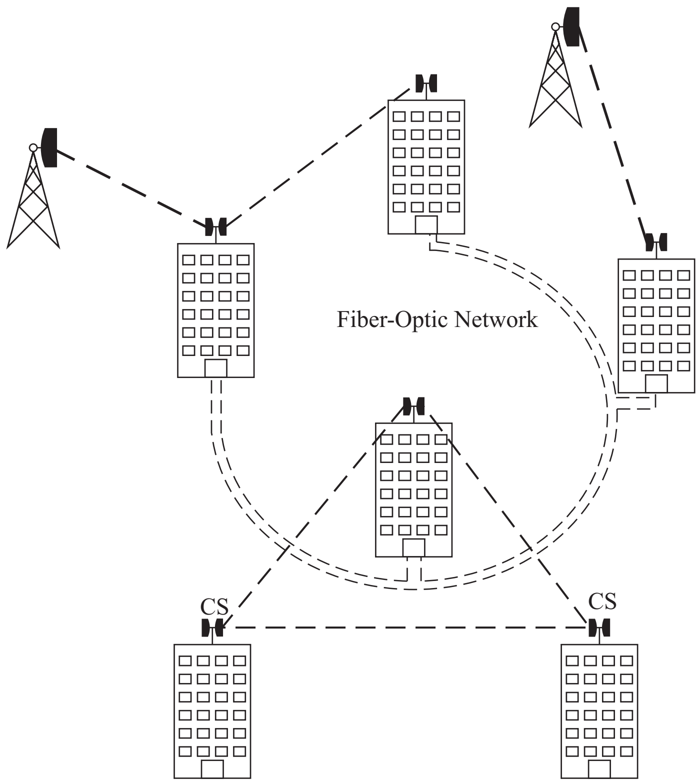

FIGURE 1.11 Microwave LOS link connections in metro and access networks.

1.5 BASIC STRUCTURE OF A FIXED SERVICE MICROWAVE LINK

Basically, a microwave LOS link is composed of a transmitting station, a receiving station, transmitting and receiving antennas, as well as the required support infrastructure, that is, a tower, to install the radiating systems.

Nodal or terminal stations of a microwave LOS link are the radiocommunication stations where the baseband (BB) payload is originated and sent to. The LOC requirement of radio links limits the maximum range between two stations. In cases where terrain irregularities or earth's curvature obstruct the LOC path between nodal stations, intermediate repeater stations will be required. There are two general types of intermediate repeater stations:

- *Passive Repeaters*: These are either simple reflecting surfaces (radioelectric mirrors) or directive antennas installed back to back through a passive transmission line. In both cases, these stations change the direction of the transmission path and are used in certain cases to avoid obstruction caused by isolated obstacles.

- *Active Repeaters*: These are radiocommunication stations that use active elements, transmitters, receivers, and radiating systems that receive, process, amplify, and transmit the signal arriving from one link hop to the next one. Depending on the processing involved, these stations can be radio frequency (RF), intermediate frequency (IF), and BB repeaters.

A hop (or link hop) in a microwave LOS link is the link section between two radio stations, either between a nodal and a repeater station or between repeater stations. A link without repeaters is a single-hop link. For obvious economical reasons, the number of hops in a link should be kept as low as possible and the hop distances should also be as short as possible.

In most application scenarios, microwave LOS links are bidirectional systems, and all the stations of the link are composed of transmitting and receiving sections. Figure 1.12 contains a block diagram of a bidirectional link with nodal and intermediate repeater stations. Figure 1.12a contains the path terrain profile illustrating how intermediate repeaters are installed to ensure LOS in all hops. Figure 1.12b shows the functional equipment blocks of the link.

The transmitter section of a link performs radio multiplexing, error correction, modulation, IF to RF frequency up-conversion, amplification and filtering functions. The receiver block, in turn, performs RF pass-band filtering, RF to IF frequency conversion, demodulation and radio de-multiplexation. Many of these functions can be integrated into common transmission and reception modules. Thus, multiplexer and demultiplexers (MULDEMs) are composed of combined radio multiplex and de-multiplexation stages; modulator demodulators combine modulation and demodulation functions and transceivers perform the frequency conversion from IF to RF and vice versa.

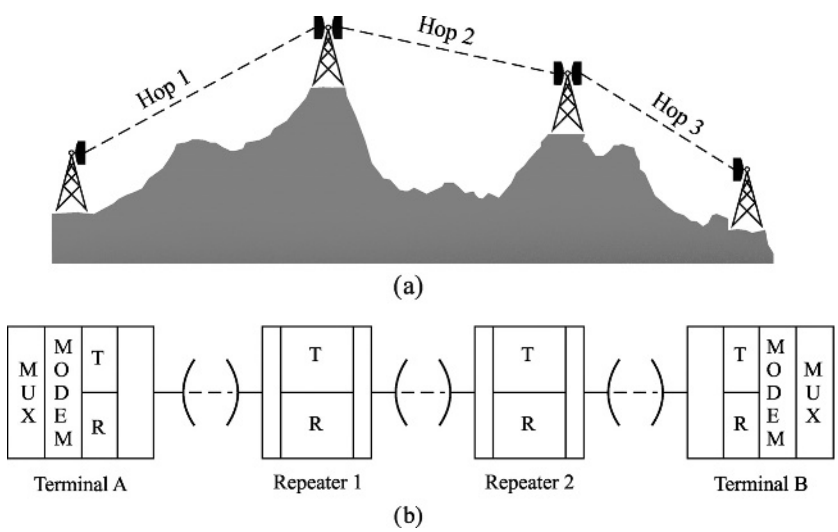

FIGURE 1.12 Building blocks of a microwave LOS link.

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As illustrated in Figure 1.12, radio links are cascaded communication systems. In consequence, any interruption caused by equipment failure or severe propagation fading affects the whole link. In order to guarantee a certain availability target of the entire system, it is common practice to install redundant modules to cope with eventual equipment failures. The propagation fading occurrences cannot be avoided in most cases, but their effect can be mitigated with diversity schemes.

A microwave LOS link with M active and N reserve (backup) radio channels is designated as an M + N system. If the link has a single radio channel without any backup, it is identified as a 1 + 0 system. Reserve radio channels and associated equipment are put into service when the link suffers an interruption. The system monitoring and management is carried out by a monitoring and control system, which performs configuration, remote control, remote command (telecommand), and supervision of all the different stations, elements, and equipment that compose the microwave LOS link.

Microwave LOS links can be part of a variety of network architectures. The usual configurations are as follows (see Figure 1.13):

- *Point-to-Point*: A link which connects two terminal stations that conveys either unidirectional or bidirectional traffic.

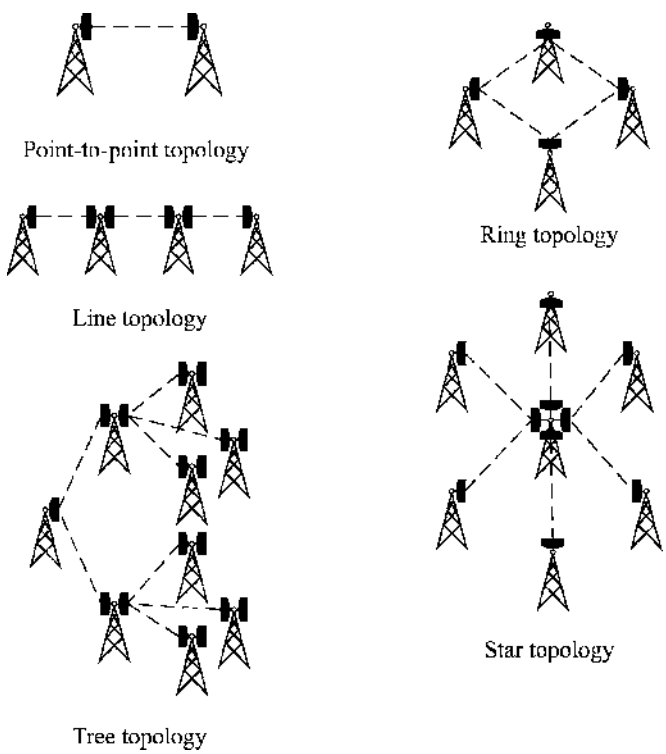

FIGURE 1.13 Microwave LOS link network topologies.

- *Line*: Each station is connected to another two (East and West), except for the nodes that are terminal stations of the entire line structure. This architecture is a cascaded composition of several point-to-point links. The nodes in this topology are usually referred as *edge nodes*.
- *Tree*: This layout is composed of a hierarchy of stations following a structure that resembles a tree. The nodes in this topology are called *aggregation nodes*, as they concentrate traffic arising from all the links connected to each node to be transmitted to the next hierarchy branch.
- *Ring*: The nodes are connected with links that form a ring. Any destination node of a ring can be reached following two paths, clockwise and counterclockwise direction.
- *Star*: All nodes of the network are connected by means of a central node.
- *Hybrid or Mesh*: This topology is a mixture of the previous layouts. Hybrid networks use a combination of other structures, so the final network architecture does not follow a dominating pattern.

1.6 SPECTRUM MANAGEMENT ASPECTS

One of the first steps when planning a microwave LOS link is the selection of the frequency band where the system will operate. The choice is not arbitrary and the radio channel plan must use resources from the available portions of the spectrum that have been allocated to the FWS by the ITU-R first and adopted with minor variations by the incumbent national or regional administration.

Usually, when requesting administrative permits for deploying a microwave LOS system, there is usually a requirement for specifying the emission bandwidth of the signals involved that, in turn, will depend on the specific channel arrangements of the selected band, the system capacity requirements, and the maximum acceptable interference levels.

It should always be kept in mind that the radio spectrum is a natural resource and as such, though reusable, is scarce. Consequently, it should be optimally used so that it can be utilized by as many as possible stations while maintaining a minimum mutual interference. For this purpose, spectrum engineering is required to manage and plan all aspects associated with the use of frequency bands for specific services. Worldwide, a relevant portion of the spectrum engineering effort is carried out by the ITU-R, which is the major international spectrum regulator. The framework for spectrum management procedures is compiled on the Radio Regulations. This document is a live compilation of the decisions taken at the World Radiocommunication Conferences. The Radio Regulations also contain Annexes, Resolutions, and Recommendations produced at the ITU-R in order to guarantee a rational, equal, efficient, and economical use of the spectrum.

World Radiocommunication Conferences are held periodically to facilitate a continuous review and, if necessary, modify the contents of Radio Regulations. In addition, Regional Radiocommunication Conferences are also called by the ITU or a group of countries, in order to agree on a specific service or frequency band. The body within the ITU-R that guarantees the application of rules and dispositions contained by the Radio Regulations is the Radiocommunication Office, which also updates and manages the Master International Frequency Register that contains worldwide frequency assignments.

1.6.1 ITU-R Radio Regulations: Spectrum Parameters and Definitions

The basic concepts and definitions related to generic radiocommunication systems are included in the first volume of the Radio Regulations. This section compiles the most relevant concepts and definitions related to FWS links, which will be later used in further chapters of this book. The list of definitions that follow regard first spectrum-related terms and second equipment-related nomenclature. The frequency spectrum-related definitions are as follows:

Frequency Band Allocation: The allocation of a given frequency band is the definition of the purpose of its use by one or more terrestrial or space radiocommunication services or the radio astronomy service under specified conditions.

Frequency Allotment: A frequency allotment is the designation of a frequency or a channel in an agreed plan, adopted by a competent conference, for use by one or more administrations for a terrestrial or space radiocommunication service in one or more identified countries or geographical areas and under specified conditions.

Frequency Assignment: A frequency assignment is an authorization given by an administration for a radio station to use a RF or RF channel under specified conditions.

Emission characteristics and equipment-related nomenclature are as follows:

Emission: An emission is a radiation produced, or the production of radiation, by a radio transmitting station. Radiation is the outward flow of energy from any source in the form of radio waves.

Unwanted Emissions: Unwanted emissions consist of spurious emissions and out-of-band emissions.

Out-of-Band Emissions: Out-of-band emissions are those on a frequency or frequencies immediately outside the necessary bandwidth, which results from the modulation process, but excluding spurious emissions.

Spurious Emission: Spurious emission is the one produced on a frequency or frequencies that are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products, and frequency conversion products, but exclude out-of-band emissions.

Assigned Frequency Band: The assigned frequency band is the frequency range within which the emission of a station is authorized; the width of the band equals the necessary bandwidth plus twice the absolute value of the frequency tolerance.

Assigned Frequency: The assigned frequency is the center of the frequency band assigned to a station.

Characteristic Frequency: The characteristic frequency is a frequency that can be easily identified and measured in a given emission. A carrier frequency may, for example, be designated as the characteristic frequency.

Reference Frequency: The reference frequency is a frequency having a fixed and specified position with respect to the assigned frequency. The displacement of this frequency with respect to the assigned frequency has the same absolute value and sign that the displacement of the characteristic frequency has with respect to the center of the frequency band occupied by the emission.

Frequency Tolerance: The frequency tolerance is the maximum permissible departure by the center frequency of the frequency band occupied by an emission from the assigned frequency or by the characteristic frequency of an emission from the reference frequency.

Necessary Bandwidth: The necessary bandwidth is, for a given class of emission, the width of the frequency band, which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions.

Occupied Bandwidth: The occupied bandwidth is the width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage $\beta/2$ of the total mean power of a given emission. Unless otherwise specified in an ITU-R Recommendation for the appropriate class of emission, the value of $\beta/2$ should be taken as 0.5%.

Peak Envelope Power: The peak envelope power of a radio transmitter is the average power supplied to the antenna transmission line by a transmitter during one RF cycle at the crest of the modulation envelope taken under normal operating conditions.

Mean Power: The mean power of a radio transmitter is the average power supplied to the antenna transmission line by a transmitter during an interval of time sufficiently long compared with the lowest frequency encountered in the modulation taken under normal operating conditions.

Carrier Power: The carrier power of a radio transmitter is the average power supplied to the antenna transmission line by a transmitter during one RF cycle taken under the condition of no modulation.

Antenna Gain: The gain of an antenna is the ratio, usually expressed in decibels, of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux density at the same distance. When not specified otherwise, the gain refers to the direction of maximum radiation. The gain may be considered for a specified polarization. Gain is usually considered relative to an ideal isotropic radiator isolated in free space conditions and it is referred as isotropic gain or absolute gain (Gi).

Equivalent Isotropically Radiated Power: The EIRP is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain).

Effective Radiated Power (ERP): The ERP in a given direction is the product of the power supplied to the antenna and its gain relative to a half-wave dipole in a given direction.

1.6.2 Frequency Allocations

The ITU-R has divided the world into three regions for regulatory purposes related to frequency allocation and associated procedures. These regions are shown in Figure 1.14 from ITU-R Radio Regulations.

The allocations of the frequency bands to radiocommunication systems in each one of the three ITU-R regions are compiled on the Table of Frequency Allocations of ITU-R. Currently, there are close to 40 different service types worldwide categorized by the ITU-R that have an entry on the Table of Frequency Allocations.

Service allocations are classified into primary and secondary. Stations associated with a secondary service should not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date. Secondary services cannot claim protection from harmful

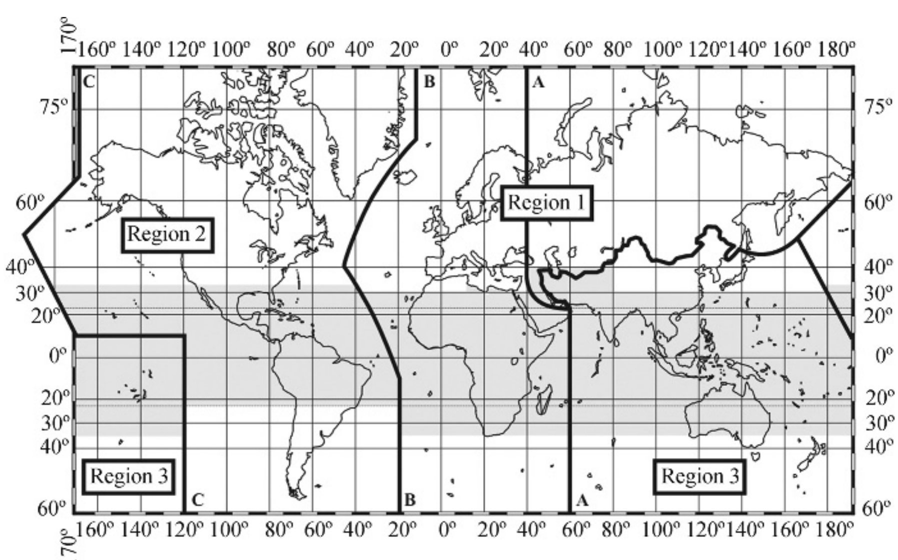

FIGURE 1.14 ITU-R regions. (*Figure Courtesy of ITU-R.*)

TABLE 1.1 ITU Frequency Bands and Global Allocations of the Fixed Service

Band Number	Band Symbol	Frequency Range (Lower Limit Excluded but Including Upper Limit)	Metric Subdivision	Fixed Service Allocation
4	VLF	3–30 kHz	Myriameter band	
5	LF	30–300 kHz	Kilometer band	
6	MF	300–3000 kHz	Hectometer band	
7	HF	3–30 MHz	Decameter band	
8	VHF	30–300 MHz	Meter band	
9	UHF	300–3000 MHz	Decimeter band	x
10	SHF	3–30 GHz	Centimeter band	x
11	EHF	30–300 GHz	Millimeter band	x
12		300–3000 GHz	Decimillimeter band	

VLF, very low frequency; LF, low frequency; MF, medium frequency; VHF, very high frequency; UHF, ultra high frequency; SHF, super high frequency; EHF, extremely high frequency

interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date. However, secondary stations can claim protection from harmful interference from stations of the same or other secondary services to which frequencies may be assigned at a later date.

Table 1.1 contains the frequency band division of the radio spectrum adopted by the ITU-R. This table includes, in relation to this book, those bands that contain global allocations for the Fixed Service.

Each one of the frequency bands allocated to the FS for use in microwave LOS links is divided according to different channel widths and a variety of possibilities for number of channels. These arrangements are described in Recommendations of the ITU-R F Series. Specifically, ITU-R Recommendation F.746 contains a useful guide of the ITU-R arrangements for microwave LOS links in different bands, with references to the documents that describe the specific arrangements of each band. The specifications for upper frequency bands have been in line with the technological developments in equipment and devices. Figure 1.15 shows the evolution in the use of HF bands during the last decades of the present and the past century.

The regulatory body that manages the use of the spectrum in the United States is the Federal Communications Commission (FCC). The FCC is a federal agency that establishes the technical specifications of radiocommunication systems and elaborates the Frequency Allocation Table for national use, based on the ITU-R's Table of Frequency Allocations.

In Europe, the Conference of European Post and Telecommunication Administrations (CEPT), through the Electronic Communications Committee (ECC), develops a common policy for regulating electronic communications, harmonizing the use of the spectrum resources at European level. All the documentation and regulatory documents produced by the ECC is distributed by the European Radiocommunications Office, which also provides detailed information about the work carried out by the ECC.

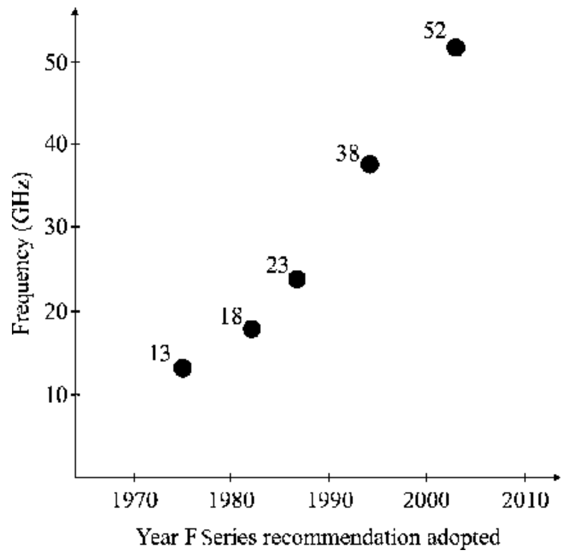

FIGURE 1.15 Evolution of the use of frequency bands for fixed service links.

1.7 FIRST APPROACH TO THE DESIGN OF A MICROWAVE LOS LINK

The design of a microwave LOS link system is a complex task that involves different calculation steps and design procedures that are (almost all of them) interrelated. Even though this topic will be described in detail in 3, 5, further chapters, a first approach to the design of a microwave LOS link should include at least the following phases and tasks:

Phase 1 Preliminary Studies. This phase involves the following generic tasks.

1. Analysis of the specifications and study of the application for which the link will be designed. This task involves an evaluation of the transport technologies upon which the link will be designed (TDM, PDH/SDH, ATM, IP, Ethernet) in relation to the capacity requirements of the application and the possible restrictions arriving from the network that the link is going to belong.
2. Study of the appropriate frequency band (in many cases, this is a specification that cannot be modified).
3. Equipment selection and equipment specification studies. Analysis of the capacities provided by different manufacturers and models, BB and multiplexation options, system upgrade and extension possibilities, diversity and redundancy schemes allowed, etc.
4. Study of the availability and error performance objectives and the allocation of a portion to the MW link in relation to the network where the system will be

installed. This task will be based on reference values found in ITU-T and ITU-R Recommendations for availability and error performance objectives unless the operator of the radio link specifies its own values from experience in previous designs on the specific geographic area.

5. First analysis of the link radio route and terrain profile. This first path analysis will identify the number of hops and the candidate sites for intermediate repeater stations, if those were required.

Phase 2 Detailed Link Design.

1. Design of an initial frequency plan. This task will propose the radio channel arrangements in each one of the hops of the link.
2. Detailed study of the radioelectric route. Intermediate repeater station choice and calculations associated with terrain profiles (antenna heights, clearance criteria, etc.).
3. Assignment of error performance objectives to the different sections (hops) of the radio link and analysis of the system threshold values.
4. Link budget design in each one of the link hops. Evaluation of system margins and preliminary decision about the use of diversity and redundancy techniques.
5. Interference analysis. Study of intrasystem interferences and optimization of the radio channel plan. Decision about the need for special antennas that might mitigate interference problems in complex frequency reuse scenarios.

Phase 3 Installation, Tests, Operation, and Maintenance.

1. Inspection of path obstacles and relevant spots in the field. Site redesign and antenna height recalculation if necessary.
2. Equipment setup and installation. System tests to evaluate background bit error rates (BBERs), system threshold checks, identification of unexpected interference problems, etc.
3. Link operation and maintenance.

The different design process blocks are depicted in Figure 1.16. The figure also contains a reference to the chapters where the different design procedures and calculations will be described in this book. The block diagram also contains an indication of the processes that are more closely related. Nevertheless, it is important to note that there are design dependencies that have not been drawn in the picture, for the sake of visual simplicity of the diagram. In fact, a microwave LOS link design should be regarded as a group of interrelated methods whose partial outputs influence practically the rest of design modules and steps.

The remaining sections of this chapter cover the basic calculations associated with the link budget evaluation, system threshold definitions, noise calculations, and preliminary introduction to interference calculations. These sections have been deliberately included in this introductory chapter due to their basic nature. Any radiocommunication engineer should be familiar to these basic concepts, as they are quite common practice in practically all radiocommunication systems.

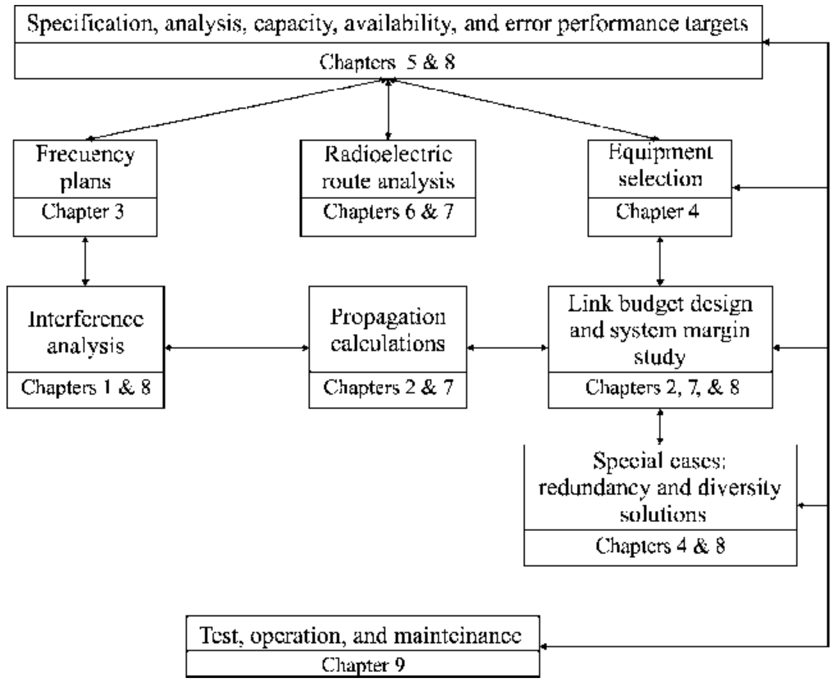

FIGURE 1.16 Simplified processes in the design of a microwave LOS link.

1.8 LINK BUDGET BASICS

1.8.1 Link Budget

The link budget of a microwave LOS link is the set of calculations that relate the available power at the receiver input with the transmitted power, the losses in transmission lines, losses in antenna distribution networks, antenna gain values, and attenuation suffered by the link signals along the propagation path.

Figure 1.17 shows a block diagram that includes all the generic elements of a radiocommunications system, from the transmitter to the receiver. This diagram is the model commonly used to illustrate the calculations involved in a link budget as well as the parameters that should be taken into account.

The block diagram contains the following elements associated with the transmission equipment:

1. Transmitter (TX).
2. Antenna distribution and coupling circuits: antenna feeder, multiplexors, etc. The interface T (physical interface) is defined between the transmitter and the antenna coupling elements.
3. Antenna circuit, which accounts for all the elements associated with losses of the antenna.

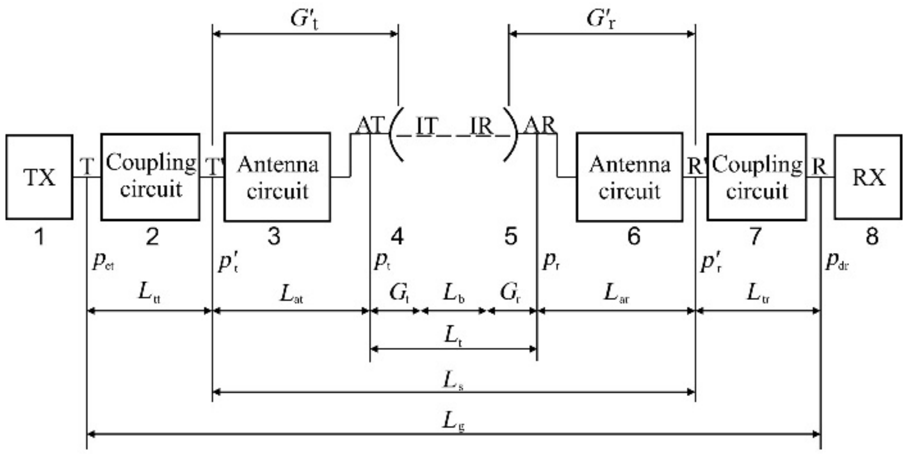

FIGURE 1.17 Model of a radiocommunication system for link budget calculation purposes.

4. Ideal directional antenna. This is a virtual block representing a lossless antenna which in combination with the antenna circuit is equivalent to the real physical antenna. The interface AT (virtual interface) is defined between the antenna circuit and the ideal antenna.

On the receiver side, the following blocks are defined:

1. Ideal lossless antenna for receiving purposes.
2. Reception antenna circuit. Equivalent to the antenna circuit in transmission. This block and the previous lossless antenna element compose the real receiving antenna.
3. Coupling circuits from the antenna to the receiver. These circuits are connected to the receiver at the physical interface R′ and are composed of duplexors, filters, transmission line sections, etc.
4. Receiver (RX).

1.8.1.1 Power Levels All the power magnitudes in the link calculation formulae are always expressed in decibels and associated logarithmic units. A compilation of the different parameters associated with power levels in a link budget is shown on Table 1.2. Absolute values are usually expressed in decibel-milliwatt units (power level relative to 1 mW).

The whole model assumes perfect impedance matching condition for all interfaces.

1.8.1.2 Gain and Losses Following the block diagram shown in Figure 1.17, Table 1.3 contains the definition of all the losses associated with the different elements of the system. All magnitudes shown are in decibels.

TABLE 1.2 Power Levels and Related Magnitudes in a Link Budget (as in Figure 1.17)

P_{tx} (dBm)	Power delivered by the transmitter to the antenna circuit
P'_t (dBm)	Power delivered to the real antenna at the input of the antenna circuit
P_t (dBm)	Virtual power delivered to the ideal lossless antenna and equivalent to the total radiated power
EIRP (dBm)	Equivalent isotropic radiated power in the direction to the receiver
P_r (dBm)	Available power (virtual) in the lossless ideal receiving antenna
P'_r (dBm)	Available power (real) at the antenna circuit output (coupling network input)
P_{rx} (dBm)	Available power at the receiver input

The losses associated with the antennas (antenna circuits), L_{at} and L_{ar}, are usually given in the form of efficiency values (η_{at}, η_{ar}) either in linear or logarithm units, as shown in equation (1.1):

$$\begin{array}{l} l_{at} = \dfrac{100}{\eta_{at}(\%)} \\ l_{ar} = \dfrac{100}{\eta_{ar}(\%)} \end{array} \quad \text{or in logarithmic units} \quad \begin{array}{l} L_{at} = 10\,\log\,(100/\eta_{at}) \\ L_{ar} = 10\,\log\,(100/\eta_{ar}) \end{array} \tag{1.1}$$

Additionally, a difference should be made between the power gain and directive gain of the antenna systems of the link. These gain values are represented by G'_t/G'_r for power gain and G_t/G_r for directive gain. Power gain values take into account the gain of the ideal antenna and reduce this value according to the antenna losses (efficiency). The basic loss, the transmission loss, and total loss are then:

$$\begin{aligned} L_t &= L_b - G_t - G_r \\ L_s &= L_t + L_{at} + L_{ar} = L_b - G'_t - G'_r \\ L_g &= L_s + L_{tt} + L_{tr} \end{aligned} \tag{1.2}$$

where L_t, L_s, and L_g have been defined in Table 1.3. In general, the losses associated with antenna circuits are usually low and power gain values are usually considered

TABLE 1.3 Losses in the Link Budget Calculation (as in Figure 1.17)

L_{tt}	Losses on the antenna distribution and coupling circuits, between T and T′ interfaces
L_{at}	Losses on the antenna circuits on the transmission side, between T′ and AT interfaces
L_{tr}	Losses on the distribution and coupling circuits connecting the antenna and the receiver, between R′ and R interfaces
L_{ar}	Losses on the antenna circuits on the receiver side, between AR and R′ interfaces
L_b	Basic propagation loss, function of the distance, frequency and propagation mechanism
L_t	Transmission loss. It is calculated as the basic propagation loss minus the ideal antenna gains (transmitter plus receiver)
L_s	System loss. It represents the difference in levels between the input to the real antenna in transmission and the output of the real antenna at the receiver side
L_g	Total loss, defined between the transmitter output and the receiver input

the same as directive gains. In this case, equation (1.2) can be rewritten as:

$$L_t = L_s = L_b - G_t - G_r \tag{1.3}$$

1.8.1.3 Link Budget Expression The link budget equation relates the available power at the receiver input with the transmitted power and all the loss sources reviewed in the previous section, including the ones associated with equipment and also those related to propagation:

$$P_{rx} = P_{tx} - L_{tt} + G_t - L_b + G_r - L_{tr} \tag{1.4}$$

where

P_{rx} (dBm) = available power level on the receiver input
P_{tx} (dBm) = power delivered by the transmitter to the antenna distribution network
L_{tt} (dB) = losses associated with the antenna distribution network (transmitter to antenna)
L_{tr} (dB) = losses associated with the antenna distribution network (antenna to receiver)
L_b (dB) = basic propagation loss
G_t (dB_i) = transmitter antenna gain (directive gain, assuming negligible antenna losses)
G_r (dB_i) = transmitter antenna gain (directive gain, assuming negligible antenna losses)

1.8.2 Propagation Losses

Under standard propagation conditions, in absence of hydrometeors or anomalous refraction behavior, and provided that the system is adequately designed to ensure adequate clearance above terrain obstacles, the basic propagation loss should equal the free space propagation loss value. Nevertheless, both rain, nonstandard refraction conditions, and other phenomena such as multipath produce fading. In each hop of a generic microwave LOS link route, the propagation loss can be divided into two components:

L_{fs} Basic free space loss
L_{bexc} Basic losses in excess to the free space loss

The free space loss formula is given by equation (1.5)

$$L_{FS} = 92.45 + 20 \log f + 20 \log d \tag{1.5}$$

where

f (GHz) = frequency
d (km) = propagation distance

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The basic losses in excess to the free space loss include all the additional losses suffered by the signal along the propagation path that cannot be associated with the free space loss. Strictly speaking, all the different excess loss components will be represented by statistic variables that will depend on how the different physical phenomena involved in propagation (refraction, diffraction, reflection, scattering, etc.) affect the signal at each moment.

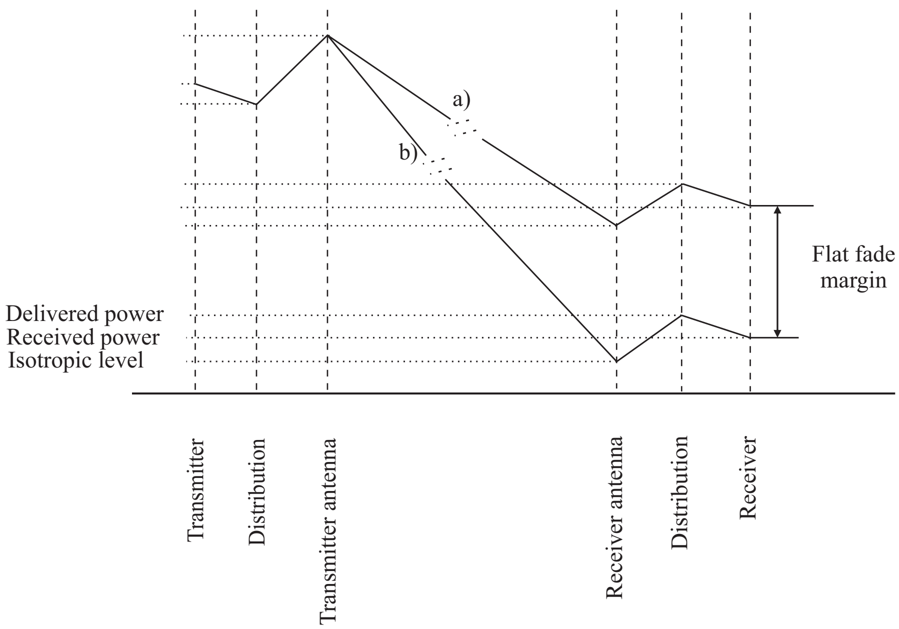
From a practical standpoint, not all the propagation losses have a variation high enough to be worth modeling as variables. Consequently, for system design purposes, the excess losses are usually divided into constant or fixed excess losses and variable excess losses. The loss sources commonly considered constant are as follows:

L_{gases}	Gas (O_2) and water vapor (H_2O) absorption
$L_{vegetation}$	Vegetation attenuation values. If necessary, this term is calculated using empirical attenuation values for different vegetation and polarization situations. Under standard system deployment conditions, if the link is designed correctly, this term should be zero.

The excess losses that are variable over time, L_{bexcv}, are those ones that show a variability that is relevant enough to be included in the link design and calculation processes. Those variable losses are usually referred as *fading*. Fading sources can be classified as follows:

$L_{diffraction}$	Diffraction in obstacles (caused by anomalous refraction, see Chapter 2).
$L_{scintillation}$	Tropospheric scintillation fading
$L_{hydrometeors}$	Fading caused by rain and other hydrometeors
$L_{multipath}$	Multipath fading, including reflection effects on earth surface and multipath originated due to various refraction phenomena in higher troposphere layers.
L_{XPD}	Depolarization losses (associated with hydrometeors and anomalous refraction)
$L_{misaligment}/L_{beam\ spreading}$	These losses are caused by anomalous refraction conditions. The refraction creates in both cases a variation of the angles of the signal at different sections of path (angle variation at the transmitter/receiver antenna, changes along the path defocusing the signal beam). This variation is independent of frequency and occurs specially on coastal regions and humid climates, where refraction phenomena are more relevant.

Figure 1.18 shows a diagram representing the power level values at different points of the link model. This type of graph is called hypsogram. The figure introduces the concept of link margin, an important concept in the system design process. In this specific case, the figure represents the difference between fixed losses (associated with free space conditions plus absorption from gases) and variable losses.



a) Fixed basic losses
- L_{fs} : Propagation basic losses (free space)
- L_{gases} : Gases and water vapor absorption
- $L_{vegetation}$: Vegetation attenuation

b) Time-varying losses in excess
- $L_{diffraction}$: Diffraction losses (anomalous refraction)
- $L_{scintillation}$: Atmospheric scintillation losses
- L_{rain}: Losses due to rain and other hydrometeors
- $L_{mutipath}$: Losses due to multipath
- $L_{beam\ spreading}$: Fading due to beam spreading

FIGURE 1.18 Hypsogram (power level diagram) in a microwave LOS link.

The equipments in real links have a certain capacity to cope with flat fading using automatic gain control (AGC) equipment that could compensate, at least partially, fading occurrences of the received signal. The benefit obtained with AGC circuits will depend on each manufacturer's compromise choice between complexity, gain, bandwidth, and associated noise and nonlinear degradations that any active circuit will introduce in a receiving system.

1.8.3 Threshold Values and Gross Fade Margin

The gross fade margin or fade margin in a link budget is the difference between the power level received in nominal conditions, that is, absence of fading, and the system threshold level associated with a specified error performance condition. The fade

TABLE 1.4 Theoretical Thresholds ($w = E_b/N_0$) Associated with Different Modulation Schemes

	E_b/N_0 (dB) at (BER = 10^{-3})	E_b/N_0 (dB) at (BER = 10^{-6})
BPSK	6.8	10.5
QPSK	6.8	10.5
4-DPSK	9.1	12.8
8-PSK	10.0	13.8
16-QAM	10.4	14.4
64-QAM	14.7	18.8
256-QAM	19.3	23.5

QPSK, quadrature phase shift keying; QAM, quadrature amplitude modulation; BPSK, binary phase shift keying; DPSK, differential phase shift keying

margin is expressed in decibels. It is obvious that the study of the receiver thresholds is a requirement for obtaining the fade margin.

The receiver threshold is the minimum power level at the input receiver that is associated with a specific BER. This parameter is usually referred as T_h and it is commonly expressed in decibel-milliwatt. Under thermal noise perturbation conditions, the threshold will depend on the modulation scheme, the bitrate, the channel coding algorithm, and the equivalent thermal noise at the receiver input. The theoretical calculation of the threshold value is based on the E_b/N_0 value associated with the BER objective. The E_b/N_0 is the relationship between the energy per bit and the spectra density of the noise. Table 1.4 shows a list of commonly used modulation schemes and associated E_b/N_0 threshold values for usual error performance objectives (10^{-3} and 10^{-6}).

Once the value of w is set, the power level threshold value is immediate, provided the bitrate R and the receiver noise figure F are known. The calculation in its linear version is:

$$w = \frac{e_b}{n_o} = \frac{T_h}{kT_o f R} \tag{1.6}$$

or in decibel units:

$$T_h(\text{dBm}) = W(\text{dB}) + F(\text{dB}) + 10 \log R(\text{bps}) - 174 \tag{1.7}$$

where

T_h = power level threshold associated with a specific BER
K = Boltzman constant
T_0 = standard temperature (usually 270°)
f = receiver noise factor (F, noise figure in decibels)
R = bitrate

TABLE 1.5 BER and ITU-R Recommendations for Threshold Calculation in Microwave LOS Links

Criteria		ITU Recommendations	BER
SESR	Availability	ITU-T: G.821, G.827 // ITU-R F.1703	10^{-3}
SESR	Error performance	ITU-T: G.826, G.828, G.829 // ITU-R F.1668	10^{-6}, $1.7 \cdot 10^{-5}$
BBER	Error performance	ITU-T: G.826, G.828, G.829 // ITU-R F.1668	10^{-12}

In practice, the threshold values are slightly higher than the ones based on theoretical expressions. Theoretical values, such as the ones shown in Table 1.4, are usually calculated for a Gaussian channel transmission model. The real propagation channel will be affected by different perturbation sources in addition to the thermal noise (interferences, phase noise in carrier recovery circuits, jitter in clock recovery modules, distortion, nonlinearities, etc.). Exception made for interference, it is assumed that the threshold values that manufacturers provide, already account for any degradation arriving from the equipment design or manufacturing tolerances.

There is a quite numerous group of ITU-R and ITU-T recommendations that provide guidance on the study of system thresholds and performance objectives. As it will be developed in further chapters, in the case of microwave LOS links, this analysis will be based on a twofold process in order to take into account unavailability and error performance. Unavailability will be associated with periods where the link is completely unusable due to equipment failures or severe propagation impairments. Error performance degradation will relate to periods where the link is operating with different degrees of degraded performance. Table 1.5 contains a first summary of the relevant recommendations for microwave LOS link design.

A new set of parameters have been deliberately introduced in Table 1.5. These parameters are used to define the criteria for evaluating availability and error performance. These parameters are the severely errored second rate and the background block error rate (or BBER) and they will be described in depth in Chapter 5. The reason for defining these parameters arises from the difficulty of a single BER value to provide accurate information about the system behavior. In the event of a certain BER value, questions would arise such as the following: How long has the BER value measured? How is the statistical distribution of the errors across the measured bit group? How accurate are bit error measurements if the system is on service? These questions make BER specifications inadequate, especially for monitoring the system quality once it is under normal operation. In order to provide a solution to these uncertainties associated with BER in operating links, the ITU has defined severely errored second rate and BBER parameters that are based on evaluating the existence of errors in blocks of transmitted bits. The advantage of this approach is the fact that most digital systems already group bites into blocks for channel coding and error correction and, at the same time, already provide mechanisms to identify erroneous blocks (where all errors have not been corrected). Thus, specifying the quality performance objectives is much more convenient for the operator of the microwave LOS link. The disadvantage is the fact that SESR and BBER are not related directly to E_b/N_0, and thus, in any case, there should be a reference BER value that is associated with the system performance objectives in order to evaluate the system power thresholds. Table 1.5 summarizes a long, complex, and controversial discussions over the past years in order to associate ITU objective parameters with BER values.

The SESR parameter from Recommendation UIT-T G.821 is 10^{-3}, which is mostly used for unavailability calculation purposes. Error performance objectives after Recommendation ITU-T G.826 (including ITU-R F.1668) are usually associated with a BER value of 10^{-6} (sometimes $1.7{\cdot}10^{-5}$). Usually, BBER is associated with a BER 10^{-12}.

The threshold parameter W will be indexed with the appropriate exponential of the BER objective; thus, T_{h3} and W_3 will be associated with a BER of 10^{-3}, T_{h6} and W_6 to 10^{-6} , T_{h5} and W_5 to $1.7{\cdot}10^{-5}$, and finally T_{h12} and W_{12} to 10^{-12}.

The manufacturer will provide the equipment thresholds under defined conditions. Should this information not be available, a common practice is the use of the reference theoretical value associated with the modulation and coding schemes and increase this threshold in 5 dB. Once the thresholds are established, the link margin calculation will be straight ahead. The gross fade margin also called thermal margin or flat fade margin for different BER thresholds (10^{-6}, $1.7{\cdot}10^{-5}$, and 10^{-12}) will be:

$$\begin{aligned} M_3 &= C - T_{\mathrm{h3}} \\ M_5 &= C - T_{\mathrm{h5}} \\ M_6 &= C - T_{\mathrm{h6}} \\ M_{12} &= C - T_{\mathrm{h12}} \end{aligned} \tag{1.8}$$

where C (dB) is the power level at the receiver input. In relation to the threshold values and system margin, the system gain can be expressed as:

$$\begin{aligned} GS_3 &= P_{\mathrm{t}} - T_{\mathrm{h3}} \\ GS_5 &= P_{\mathrm{t}} - T_{\mathrm{h5}} \\ GS_6 &= P_{\mathrm{t}} - T_{\mathrm{h6}} \\ GS_{12} &= P_{\mathrm{t}} - T_{\mathrm{h12}} \end{aligned} \tag{1.9}$$

The system gain is a parameter usually provided by the manufacturer of microwave LOS link equipment that enables a fast estimation of the link length and antenna gain requirements.

1.9 NOISE

When analyzing the design or the performance of a radiocommunication system, in addition to the study of the fading associated with propagation phenomena in the atmosphere, it is necessary to extend the study for taking into account additional performance degradation caused by thermal noise and interference. Special countermeasures might be necessary to cope with these additional sources of impairment and reduce their impact the on system performance.

The radio noise received by a radiocommunication system is a random process, which is associated with RF radio noise signals that do not convey any information;

although, in certain situations, it might have associated information about its source, nature, and location, and there is a possibility that might be superimposed on or combined with the wanted signal. The ITU-R Recommendation P.372 provides radio noise reference data that are classified depending upon the noise source type:

- Noise from natural sources, such as space radioelectric sources, earth surface and other obstacles intersecting the antenna beam, noise originated by lightning, and noise emissions from hydrometeors and atmospheric gases.
- Man-made noise or artificial noise, which is the aggregation of different unwanted emissions from electric machines, electric and electronic equipment, energy transmission lines, internal combustion engine switching, etc. As opposed to noise arriving from natural sources, that has a practically flat frequency response, man-made noise is lower as the frequency increases. In consequence, it is only considered for practical designs below 1 GHz.

The noise becomes an impairment that imposes a limit to the performance to any radiocommunications system. The evaluation of its influence is carried out through the normalized total noise power level, which includes the noise received by the antenna, the noise generated by the antenna and the distribution network, and the internal noise of the receiver. If the network net gain is equivalent to zero decibel, the normalized power can be expressed by the general equation (1.10). This equation is linear so the net gain is considered to be 1.

$$p_n = kT_0bf \tag{1.10}$$

where

k = Boltzmann's constant $1.38 \cdot 10^{-23}$ J/K
T_0 = reference (standard) temperature (°K), usually 290°K
b = receiver noise equivalent bandwidth (Hz)
f = receiver system noise factor

Equation (1.10) can be expressed in logarithmic units as follows:

$$P_n = F + B - 204 \tag{1.11}$$

where

P_n = noise available power (dBW)
B = 10 log b (dBHz)
-204 = 10 log $k\ t_0$ (dBW/Hz)
F = noise figure of the receiving system (dB)

The noise factor of the receiving system, f, is composed of a number of noise sources in the receiver chain. This parameter should include both the noise coming from outside and internal noise of the system as mentioned in previous paragraphs. The generic calculation method of the system noise factor follows.

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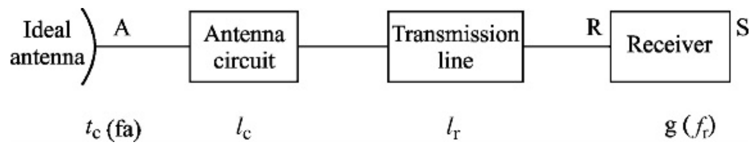

FIGURE 1.19 General radiocommunications receiver model for noise calculations.

The general model for noise calculations in a radiocommunications receiver is illustrated in Figure 1.19.

The model has three interfaces that are relevant for the calculation process:

- Interface "A": The ideal antenna output.
- Interface "R": RF receiver input.
- Interface "S": Receiver output.

The usual reference point to calculate noise is the input of the ideal equivalent receiver lossless antenna. This is a virtual interface due to the loss-free nature of the device because the terminals of this losseless antenna do not exist physically. For receivers free from spurious responses, the system noise factor is given by equation (1.12):

$$f = f_a + (f_c - 1) + l_c(f_t - 1) + l_c l_t (f_r - 1) \tag{1.12}$$

where f_a is the external noise factor defined by equation (1.13):

$$f_a = \frac{p_{nA}}{kt_0 b} \tag{1.13}$$

and the rest of involved parameters are

p_{nA} = available noise power from an equivalent lossless antenna
l_c = antenna circuit loss (available input power/available output power)
l_r = transmission line loss (available input power/available output power)
f_r = receiver noise factor
f_c = noise factor associated with the antenna circuit losses
f_t = noise factor associated with the transmission line losses
t_c = actual temperature of the antenna and nearby ground (°K)
t_t = actual temperature of the transmission line (°K)

$$f_c = 1 + (l_c - 1)\left(\frac{t_c}{t_0}\right) \tag{1.14}$$

$$f_t = 1 + (l_t - 1)\left(\frac{t_t}{t_0}\right) \tag{1.15}$$

if $t_c = t_t = t_0$, equation (1.12) simplifies to:

$$f = f_a - 1 + f_c f_t f_r \tag{1.16}$$

1.10 INTERFERENCES

Interference is defined by the ITU-R as the effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system (microwave LOS link), manifested by any performance degradation, misinterpretation, or loss of information that could be extracted in the absence of such unwanted energy.

There have been defined three levels of interference for administrative purposes: permissible, accepted, and harmful interference. Permissible interference describes a level of disturbance, which in the given conditions involves degradation of reception quality to an extent considered insignificant, but which must be taken into account in the planning of systems. The level of permissible interference is usually laid down in ITU-R Recommendations and other international agreements. Acceptable interference describes a higher level of interference involving a moderate degradation of reception quality which in given conditions is deemed to be acceptable by the administrations concerned. The third term describes a level of interference that seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service. Additional interference classifications can be found in ITU-R literature:

- Intrasystem, when the interference source and the interfered system are the same.
- Intersystem, where interfered and interfering are different systems.
- Simple interference, when there is a single interference source.
- Multiple interferences, when the interference is produced by multiple sources.
- Co-channel. The interference signal is produced in the same carrier frequency as the one used by the wanted signal, when the same radio channel is used by two or more emissions.
- Adjacent channel interference. The frequency of the interfering signal corresponds to adjacent contiguous channels. An adjacent channel is, in a given set of radio channels, the RF channel which characteristic frequency is situated next above or next below that of a given channel.

The degradation produced in the system performance caused by interference implies a higher required C/N ratio to maintain the system error performance objectives. The parameter usually employed to characterize interferences is the carrier to interference (C/I) ratio and is defined as the ratio between the level of the wanted signal and the interference power level (aggregate power in the case of multiple interference sources).

Interference analysis will be based on evaluating the C/I ratios between the interfering and interfered systems at the receiver side and ensure that those ratios are not below the specified minimum C/I threshold. The C/I calculation will be associated with the evaluation of possible radio channel frequency arrangements. If a selected radio channel scheme provides C/I ratios below the threshold, different countermeasures are possible: changing the channel scheme, using special antennas, etc. The minimum C/I ratio will be provided by the equipment manufacturer.

Interference calculations play a relevant role in applications with high link density, especially in urban areas, metro networks, mobile cellular networks, etc. The detailed study of interference calculation procedures will be covered in Chapter 8.

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