WIRELESS TERRESTRIAL COMMUNICATIONS: NON-TELEPHONY-ORIENTED TECHNOLOGIES

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Contents

Summary

This chapter provides an overview of non-telephony-oriented wireless communication systems. We present the main techniques employed or under study, with special emphasis on the emerging technologies that are changing the mobile wireless communications capability from voice applications to broadband multimedia, towards the targeted “Multimedia Wireless Communications Anytime and Anywhere”. The topic is vast and changing rapidly, and consequently this brief chapter cannot be exhausting. For this reason the reader who wants to know more is invited to refer to specific journals covering wireless communications, mainly by the Institute of Electrical and Electronic Engineers (IEEE), some listed at the end of this chapter, which provide up-to-date research results or tutorial overviews of the latest developments.

In this chapter we first review in Section 1 some basic facts about wireless communications, including technologies such as multiple antennas and multicarrier modulation. In Section 2 we describe the main characteristics of current wireless systems, with a discussion on possible evolutions towards cognitive radio.

This chapter assumes the reader is familiar with basic concepts of electrical communication systems.

1. Technical Challenges in Wireless Communications

1.1. Data Rates, Mobility and Area Coverage

Wireless communications have important peculiarities that must be clearly identified, so to avoid applying to this kind of systems some concepts or solutions valid for cables or fibers, that could be not suitable for wireless.

Mobile communication systems aim to provide to the mobile user the same services as those provided by wired networks. However, the presence of important channel impairments, the scarceness of the radio resource and mobility impose severe limitations to the quality of service (QoS) in terms of data rates and area coverage. The trade-off between data rates and users' mobility results in specific solutions for different application scenarios. For example we report in Figure 1 a graph comparing some current wireless technologies in a plane mobility vs. data rate.

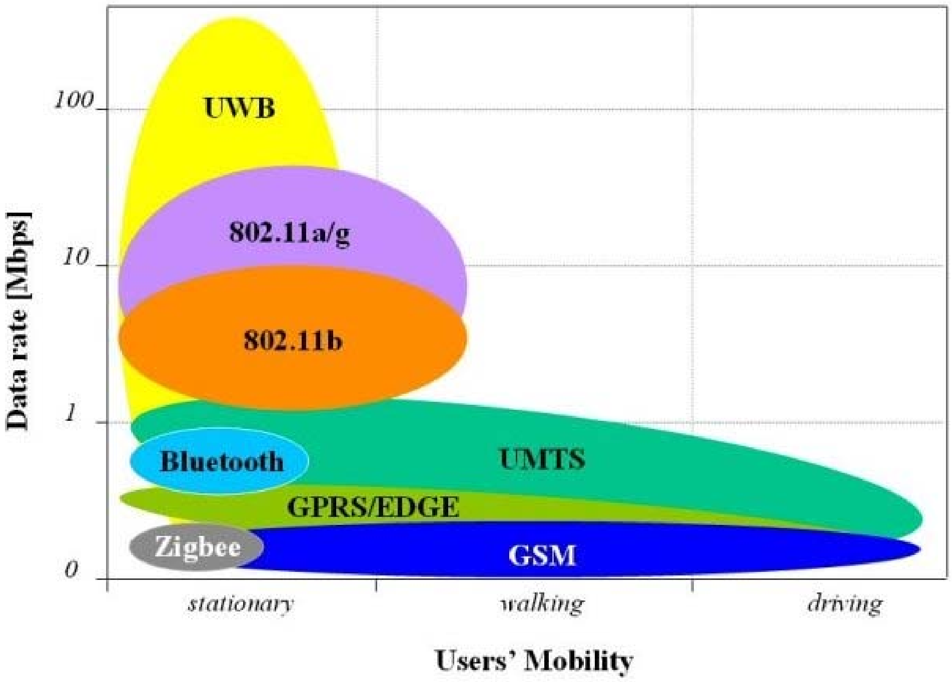

Figure 1. Comparison of some wireless communication systems.

It is worthwhile to remark that there is a strong relationship between data rates, area coverage and mobility. In mobile cellular communication systems small cells are necessary in order to achieve high data rates. At the same time small cells imply efficient handover mechanisms and implementations, that are more and more demanding as the users' speed increases.

Hence, a traditional way to categorize digital wireless networks operating worldwide is based on the distinction between **cellular networks**, carrying voice calls principally and with extensive area coverage, and **personal, local and metropolitan area networks (WPAN, WLAN, WMAN)**. However, the evolution of the latest generation of cellular networks with the possibility to provide multimedia content to the mobile user on one side, and the extension of the area coverage by using several WLAN or WMAN spots plus the possibility to carry voice over IP on the other, are somewhat making the distinction less clear from this perspective. Another taxonomy could be based on the distinction for the usage of the radio spectrum, with licensed wireless applications such as cellular GSM and UMTS systems, opposed to systems using unlicensed bands such as WLAN and WPAN.

1.2. Wireless Channel Characteristics

The wireless radio channel is the main cause of the profound difference between wireless and wired communication systems. We can schematize the impairments as due to thermal noise (related to the physics of circuits and apparatus, hence unavoidable), to signal power attenuation (related to the distance between transmitting and receiving antennas), to multi-path propagation (due to the presence of more rays arriving at the receiving antenna after reflection, diffraction and scattering), and to interfering signals (related to the scarcity of the radio spectrum and the consequent need to use the same spectrum band for several users). Moreover, for mobile radio systems where users are moving, the radio channel changes in an unpredictable way. In this subsection we will address only path loss and multipath for a single transmitter -single receiver scenario, while interference issues are discussed in subsection 1.5.

Path loss is due to dissipation of the power radiated by the transmitting antenna. Assume now an ideal free-space environment, where there are no obstructions between the transmitter and the receiver so that the signal propagates along a straight line. This situation is also called line-of-sight (LOS) channel. In this case, the received signal power, P_r, is related to the transmitted signal power, P_t, and to the link distance, d, by $P_\mathrm{r} = \alpha P_\mathrm{t} d^{-2}$ where the constant α depends on the carrier wavelength and on the antenna directional gains [1]–[4].

Unfortunately, in many cases we cannot use this simple LOS model for the radio channel; in fact, the radiated electromagnetic field is diffracted, reflected, and scattered by a multiplicity of obstacles, such as trees and walls, buildings, vehicles, etc. before reaching the mobile wireless receiver. The presence of objects and obstacles in the environment produces at the receiving antenna several copies of the transmitted signal. Another important phenomenon that can be observed for high speed users is the frequency shift of the received signal due to Doppler effect.

Without going into the details of propagation, an instructive example of scenario is depicted in Figure 2. Here we can distinguish two different phenomena. The first is related to the power loss due to the presence of obstructing objects, and is usually modeled by means of a deterministic path loss (related to distance d and to a quite broad classification of the environment) with, superimposed, a random variation of power, the so-called shadowing. This random fluctuation is caused by variations in the obstructions (terrain obstruction such as hills, man made obstructions such as buildings,...), and the result is that the received signal power can vary considerably at different locations, even though at the same radial distance from the transmitter. This effect is often referred to as **large-scale propagation effect**, since it describes variations that can be observed moving the receiver over a length of the order of the dimension of the obstacles obstructing the propagation (10 - 100 m for outdoor, less for indoor communication). The statistic of this slow variation is well described by the log-normal distribution [1]–[3].

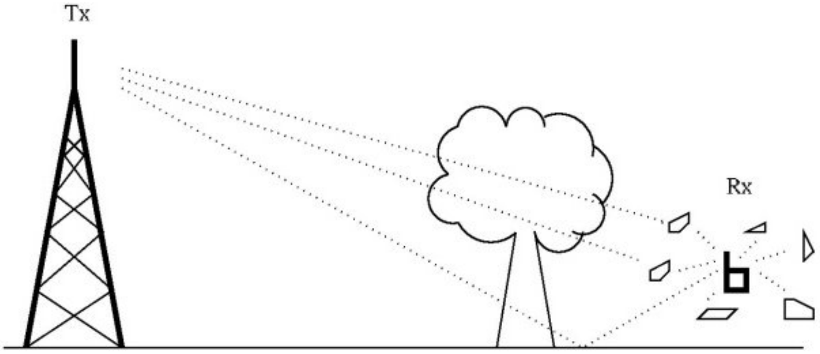

Figure 2. Example of wireless communication including path loss, shadowing and multipath.

A second effect is related to the presence of many objects surrounding the antennas, acting as scatterers: as a result, instead of one path, we have a multipath channel. Signals arriving from different paths can add constructively or destructively, depending on their relative phases; these are given by reflections and by the delays associated to each path. Now, denote by $c=3\times10^8$ m/s the light speed and assume we are transmitting an unmodulated carrier with frequency f_0 and wavelength $\lambda = c/f_0$. Let us first focus on a particular path, and observe that we have a phase variation of π radians when we move the receiver position by half a wavelength, $\lambda/2$, along the direction of the wave. If we assume more paths coming from different directions, we can understand why, in the presence of multipath, a displacement of the order of λ in the receiver antenna position or in the position of the surrounding objects causes different changes in the phases of the paths, that can result in a dramatic variation in the overall received power [1]–[3]. Just to give an idea of the relevance of this phenomenon we report in Table 1 the wavelengths for some carrier frequencies of interest. Since, as can be noted from this table, a change in the position of user or of surrounding objects of few centimeters can cause a large fluctuation in the received power; this effect is often referred to as **small-scale propagation effect**.

Carrier Frequency	Wavelength
900 MHz	33 cm
1800 MHz	16.7 cm
2400 MHz	12.5 cm

5 GHz	6 cm
10 GHz	3 cm

Table 1. Frequencies and Wavelengths

We report in Figure 3 a typical behavior of the received power for a carrier frequency of 2.4 GHz, where variations of tenths of dBs can be observed due to multipath. In the same figure it is also shown the average of the received power over a window of few wavelengths: by averaging we remove the small scale propagation effect; thus, the behavior of this average power can be described in terms of shadowing on top of the power as predicted by path loss models.

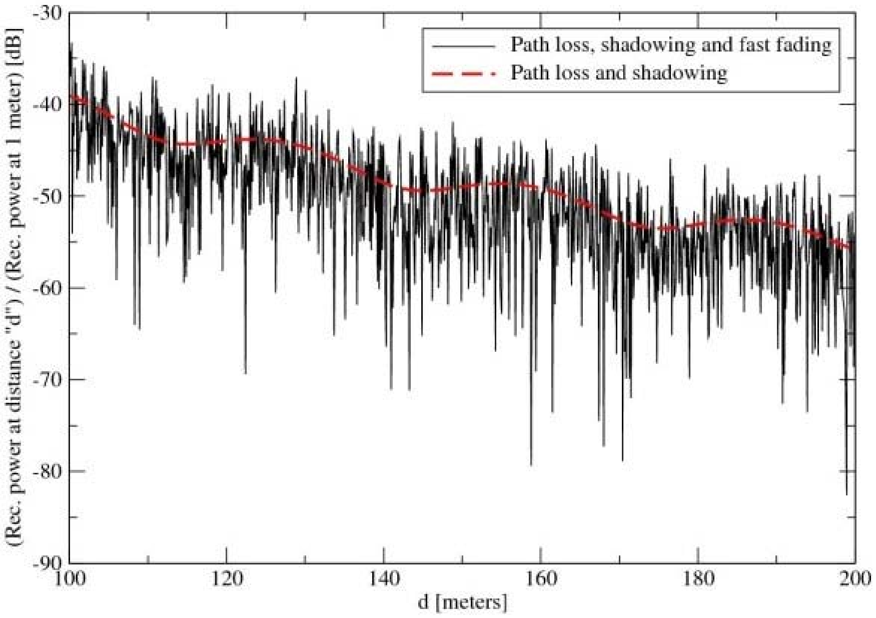

Figure 3. Example of received power (normalized, in dB), including fast fading, shadowing and path-loss for a carrier frequency of 2.4 GHz. The smoother curve is the large scale propagation effect due to path-loss and shadowing, obtained by averaging over few wavelengths.

1.3. Multiple Antenna Systems: Diversity, Interference Mitigation, MIMO

We have just shown that one of the major problems in wireless communications is the received power fluctuation due to multipath. To overcome this problem, diversity techniques can be employed. Diversity systems properly combine different copies of the same information, copies subject to possibly independent fading, so to minimize the probability of a reception failure. Diversity can be achieved by properly exploiting time (e.g. by error correcting codes and interleaving), frequency (e.g. by frequency-hopping and error correcting codes) or space (with multiple antennas).

In this regard, over the last several decades multiple antennas have been mainly used to combat fast fading, since the increase in diversity order provided by diversity techniques enable robust communications in fading environment [5]. When multiple antennas are used to counteract fast fading the advantage is in an increased robustness to the effects of multipath. For example, with one transmitting antenna we can use two receive antennas at the receiver (Single Input -Multiple Output, SIMO, see Figure 4) and pick in each instant the output of the antenna with the strongest signal power level. If the receiving antenna elements are sufficiently spaced apart, the fading can be assumed independent on the two antennas. Hence, if $p<1$ is the probability that one antenna is in a deep fade, the probability that both antennas are in a deep fade and therefore that the communication is degraded is $p^2 < p$. In this case we are exploiting the spatial dimension to achieve a **diversity gain**.

If diversity is well known since many years and employed in reception (receive diversity), there is an interest in understanding if it is possible to have diversity even with **multiple transmitting antennas** (and possibly one receiving antenna, Multiple Input -Single Output, MISO, see Figure 4). This scenario arises for example in the down-link (DL) in mobile cellular systems, that is, in the link between the radio base station (BS) and the mobile user. In fact, putting more antenna elements on the BS is easy, but doing the same on the user terminal is not easy because of space limitations [6], [7].

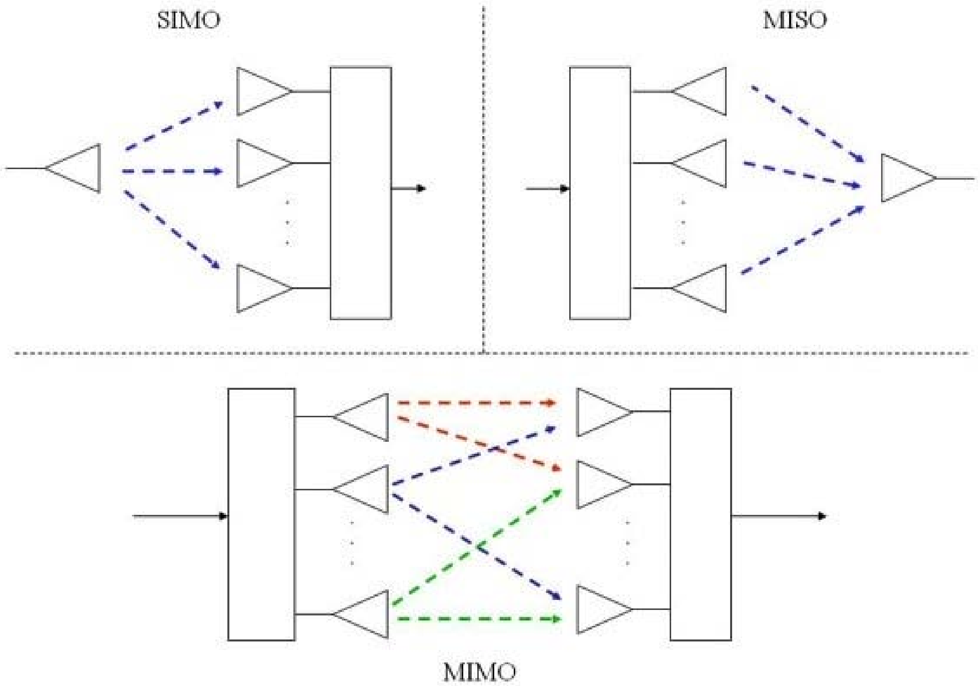

Figure 4 Single Input - Multiple Output, Multiple Input - Single Output, Multiple Input - Multiple Output

Only recently a technique has been invented to provide diversity with multiple transmitting antennas (transmit diversity). Transmit diversity is one of the novel techniques introduced in cellular mobile communications third generation standards [8].

Another well known possibility is to use smart antennas to mitigate the effect on co-channel interference. Simple examples for interference reduction are sectored antennas and multibeam antenna systems. A more advanced technique consists in adopting multiple antennas elements at the receiver with proper weights (e.g. to modify the radiation diagram if signals have a clear direction of arrival; with dense multipath, where rays come from many directions, this geometric interpretation is not useful) in order to maximize the desired output signal power, while reducing as much as possible interfering signals. The usage of smart antennas to reduce co-channel interference has a strong impact on the system capacity [9], [10].

In the last few years it has been also recognized that the capacity (in terms of bps/Hz) of wireless communication links can be increased by using multiple antennas both at the transmitter and at the receiver (Multiple Input -Multiple Output, MIMO, see Figure 4), so exploiting the spatial dimension to construct virtual parallel channels [5], [11]–[14]. Motivated by theoretical capacity analysis, the increasing demand for higher capacity has brought to the proposal of practical transmission schemes based on MIMO, where different symbols are simultaneously transmitted in order to achieve high spectral efficiencies. These schemes are known as high spectral efficiency MIMO systems. Toward achieving these capacities, a promising transmission system, called D-BLAST (Diagonal-Bell Laboratories Layered Space-Time), has been proposed [11]. This scheme is able to provide a high spectral efficiency in a rich and quasi-static scattering environment. Owing to the large computational complexity required for this scheme, a simplified version, called V-BLAST (Vertical BLAST) has been proposed in [15]. The large spectral efficiency of transmission systems based on MIMO is due to their capacity to exploit the spatial dimension, in environments characterized by rich scattering, allowing high spectral efficiencies with an important **multiplexing** advantage [16], [17].

1.4. Modulation and Error Control Techniques

The radio resource is so limited and precious that it must be used with the maximum possible efficiency. In this regard, one important parameter is the number of bit/s (bps) per frequency units we are able to transmit, that is, the spectral efficiency in terms of bps/Hz [18]. From basic communication theory we recall that a modulation format with L points in the constellation can transmit $\log_2 L$ bps/Hz. For instance, the theoretical spectral efficiency of Binary Phase Shift Keying (BPSK) is 1 bps/Hz, and for Quaternary Phase Shift Keying (QPSK) is 2 bps/Hz. From this perspective it seems convenient to use higher order modulations such as, e.g., 64QAM (Quadrature Amplitude Modulation), giving 6 bps/Hz. Unfortunately, the requirements in terms of link-budget are more strict as the modulation order increases, and the wireless channel impairments are so severe that the difficulties in demodulating these high order constellation signals increases with the data rate. Indeed, by increasing the data rate the signal band increases, and so increases the distortion due to the presence of multipath. One possible solution to counteract the channel distortion due to multipath consists in subdividing the available band in several sub-bands, over which the channel is approximately nondistorting. Over each sub-band a low data rate signal can be transmitted with the maximum possible constellation size such as BPSK, QPSK, 16QAM, depending for instance on the channel quality for that sub-channel. By multiplexing all sub-channels an high data rate is achieved. This is the idea behind the techniques called **multicarrier modulation**, like Orthogonal Frequency Division Multiplexing (OFDM), that constitutes one of the most important advances for wide-band wireless communication systems.

Moreover, the presence of severe channel impairments requires the adoption of powerful error correcting codes (channel codes) to recover errors introduced by the wireless channel. So, the actual spectral efficiency must include the redundancy added for error correction. The most important error correcting codes in wireless applications are convolutional codes, turbo codes and Low-Density Parity Check Codes (LDPCC).

Spectral efficiency is further reduced due to the redundancy introduced by the error correcting code. So, for example, a rate 1/2 channel code with QPSK gives only 1 bps/Hz. If the target would be for example 1 Gbps, this means that a frequency bandwidth of 1 GHz would be needed! If we realize that the radio spectrum ranges from few hundreds of KHz to few GHz in total (for all applications), it is apparent that in order to target wireless Gbps systems (clearly for non-telephony applications) we must resort to higher spectral efficiencies.

Indeed, the answer for high data rates in wireless systems is constituted by multiple antenna systems (MIMO), as discussed in the previous section. With MIMO it is possible to reach very high spectral efficiency taking advantage of the scattering, to obtain as many virtual parallel channels as the minimum between the number of transmitting and receiving antennas. For example, a 3×3 MIMO (3 transmitting and 3 receiving antennas) with QPSK can achieve a spectral efficiency of 6 bps/Hz. MIMO technologies are thus of extreme importance for high data rates wireless systems [13], [17].

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Biographical Sketches

Marco Chiani was born in Rimini, Italy, in April 1964. He received the Dr. Ing. degree (*magna cum laude*) in electronic engineering and the Ph.D. degree in electronic and computer science from the University of Bologna, Bologna, Italy, in 1989 and 1993, respectively. He is a Full Professor at the II Engineering Faculty, University of Bologna, where he is the Chair in Telecommunication. During the summer of 2001, he was a Visiting Scientist at AT&T Research Laboratories, Middletown, NJ. He presently holds a Research Affiliate appointment at the Massachusetts Institute of Technology (MIT), Cambridge. His research interests include wireless communication systems, MIMO systems, wireless multimedia, low-density parity-check codes (LDPCC), and UWB. Under the European research program PROMETHEUS he has worked on short-range millimeter wave communication systems for Advanced Road Transport Telematics. He is also leading the research unit of CNIT/University of Bologna on Joint Source and Channel Coding for wireless video (IST FP6, project Phoenix) and is a consultant to the

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