1

Introduction

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1.1 Introduction

Over the last 20 years personal computers have developed as a mass consumer product which, coupled with the growth in widespread broadband access, offers users a multiplicity of services. The Internet is an enormous source of information (both valid and invalid) that has evolved into a virtual store, a library, a chat-room and a playground, and has enabled novel means of interacting. The simple email service is an example of how material streams (transport of letters, documents, etc.) have been replaced by information streams. These issues are leading to fundamental changes in how we do things.

A further significant step in the 'digital revolution' has been the demand for mobility, the so called *anyone, anywhere, anytime* mentality. Over the world digital mobile telephony has been a huge success. In particular, in Europe, the foundation was laid when 13 countries agreed to adopt a single digital standard for cellular mobile communications (The Memorandum of Understanding (MoU) signed on 7 September 1987 in Copenhagen). The development of the Global System for Mobile communications (GSM) followed, and the historic milestone of 1 billion mobile subscribers was reached in 2000 (Eylert, 2000). It is predicted that by the year 2010 there will be more than 1.7 billion terrestrial mobile subscribers worldwide. In addition, we have seen the wide deployment of WLAN (wireless local area network) technology, the deployment of W-CDMA (wideband code division multiple access) systems worldwide and their enhancement to HSPA (high speed packet access) offering increasing data rates, with peak downlink data rates of approximately 14 Mbps likely to be available in 2007. Other new systems that promise high data rates *and* large coverage have appeared such

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as WiMAX (worldwide interoperability for microwave access) (Ghosh et al., 2005).

It is widely recognised that the future challenge is to merge the data-oriented services prevalent on the Internet with wireless communication to fulfil the vision of *anyone*, *anytime* and *anywhere* (Mohr, 1998). Indeed this is already happening with mobile operators experimenting with offering TV services over their network, broadcasters offering communication and data services, and traditional fixed operators moving into the wireless access space.

It could be argued that the first step into the area of wireless data applications was taken by the standardisation of the Universal Mobile Telecommunication System (UMTS)† in Europe and the equivalent WCDMA system in Japan. These systems aim to provide 144 kbps in vehicular environments, 384 kbps in outdoor to indoor environments and 2 Mbps in indoor or pico-cell environments (low mobility populations) (Mohr, 1998). The extension of these services to HSDPA (high speed downlink packet access), (initial deployments in 2006), and planned extensions to HSUPA (high speed uplink packet access) and the long term evaluation of 3GPP (3rd generation partnership project) will ultimately push peak data rates to 100 Mbps in the downlink. The pace is continuing with many researchers in academia and industry discussing requirements with respect to fourth generation wireless communication systems, some have already appeared in the literature, (see, e.g. (Mohr, 2002; Yamao et al., 2000)). Yet today the predominant service over existing digital wireless systems is speech, with its unique property that it requires a symmetric full duplex channel, and instant messaging, rather than true data services. The radio-frequency spectrum has become an expensive commodity. In the UK, for example, a sum equivalent to US$154 per citizen was paid for 2×15 MHz radio-frequency spectrum for UMTS (Sidenbladh, 2000). In order to use the radio-frequency spectrum efficiently and at the same time meet the requirements of future wireless communication systems, a high degree of flexibility is required (Luediger and Zeisberg, 2000). As a result, a single radio-channel access interface which is tailored to the needs of a specific service will not fulfil the extended requirements efficiently. Therefore, new radio interface concepts have to be investigated which, for example, is something that is done as part of the European WINNER (Wireless World Initiative New Radio) project (Acx et al., 2006; Klang, 2006).

When it comes to achieving two way communication, two basic methods can be distinguished: frequency-division duplex (FDD) and time division-

† Sometimes also referred to as universal mobile telecommunications services (Holma and Toskala, 2000).

duplex (TDD). The TDD technique has primarily been used for cordless, noncellular and hence short-range communication. Due to the unique properties of TDD, as, for example, the simplicity to arrange channel asymmetry, it was considered as a potential candidate for wireless packet data services (Povey et al., 1997). On the 29 January 1998 in Paris it was decided that the TDD technique in combination with TDMA (time division multiple access) and CDMA (code division multiple access) will be used in UMTS as part of a multi-mode air-interface. Little attention has been paid to this system during the initial deployment phase of UMTS, but it enjoys increasing interest for services such as mobile broadband and mobile TV (television).

With an ever-increasing demand for packet-data services, such as Web browsing and media streaming, data traffic on the air interface will soon exceed the amount of voice traffic. While voice traffic causes a symmetric load on uplink and downlink, this clearly does not hold true for packet data traffic. In general, the latter requires variable channel asymmetry support with respect to uplink and downlink traffic, at least on an instantaneous basis. Methods such as HSDPA used in UMTS (UTRA-FDD) only partially solve this problem as this method, for example, does not support fast file uploads. Hence further system amendments such as HSUPA are currently being considered.

In addition to its flexible support of traffic asymmetry, only the TDD mode offers an efficient and flexible support for ad-hoc or multi-hop communication. This is significant because a hybrid form of cellular and ad-hoc mode operation offers the most promising solution to cater for the high-data rates and the highly imbalanced traffic of future wireless systems. This stems from the fact that in cellular systems with high data-rate transmission, the cell range shrinks significantly, which, in turn, would require a large number of base stations to avoid coverage 'dead zones'. This problem already exists in UMTS, and it will become more important with the envisaged high data rates of next-generation wireless systems.

As a conclusion, an air interface for the next generation wireless systems is envisaged to employ the TDD mode. In fact, WLAN systems have successfully demonstrated the deployment of TDD in a hot-spot environment for packet data transmission. However, if the TDD mode is used in a cellular context some TDD-specific issues have to be addressed. Due to the fact that uplink and downlink transmission is at the same frequency band additional interference might occur, namely mobile-to-mobile and base-to-base interference, the extent of which being dependent on cell specific channel asymmetry and synchronisation. These additional interference sources may cause severe capacity losses. But it has been shown that simple dynamic channel assignment (DCA) algorithms, (Haas et al., 2000a, 2002; Haas and McLaughlin, 2001a,b) can be found which avoid capacity losses - in fact, it has been demonstrated that in some cases capacity in a cellular TDD system can even be higher than in an equivalent FDD system

1.2 The multi-user access

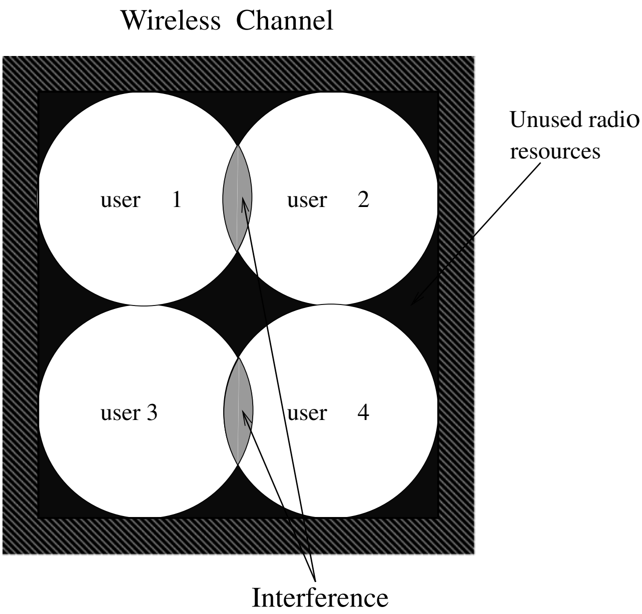

Fig. 1.1. The principles of multi user access.

The basic mechanism of the communication system that will be considered in much of this book is that a set of entities (users) access a common medium which, in this case, is the radio channel. This concept is depicted schematically in Figure 1.1. The frequency spectrum or bandwidth that is allocated to a certain system is a limited resource, which is indicated by the rectangular frame. In general, there are many coexisting wireless systems. In order to avoid interference to and from other systems a certain level of protection is required. This is indicated by the dark, shaded frame. The aim is to accommodate as many simultaneously active users as possible (capacity) within the limited total radio resource where each user transmits the highest possible number of bits per unit time and per unit bandwidth. In the example, four users are considered each of whom requires an equivalent fraction of the total radio resource (illustrated by a circle), i.e. the bandwidth is the same for each user. In the picture, the size of the circles and hence the required radio capacity are constant. In real systems the size may be time variant (which may be visualised with breathing circles in Figure 1.1). Consider, for example, a speech service and periods when a speaker is silent. There is then no requirement to transmit data and thus the size of the circle would shrink to merely a single point in the space. An ideal multiple-access technique supports the time-variant radio capacity because this means that, at any given time, only those resources which are allocated are those which are actually required. Consequently, situations are avoided where more capacity is allocated than would actually be required.

If the system is not designed carefully, users or mobile stations (MSs) will *interfere* with each other (the intersection of circles). Therefore, either the interference is eliminated via signal processing algorithms, if possible, or each user gets some extra protection which, in the illustration, is equivalent to moving users apart. This measure, however, results in *unused radio resources* which, considering the immense costs for the radio frequency spectrum, is inefficient. Therefore, the aim is to accommodate as many users as possible (minimising the area not covered with circles) while keeping the interference at a tolerable level.

Interference in a *cellular* system can be categorised as:

- Multiple access interference (MAI) is the interference that results from simultaneous transmissions in a multipoint-to-point or point-to-multipoint topology when orthogonality does not exist.
- Adjacent channel interference (ACI) is the interference that results from simultaneous transmissions in adjacent frequency bands or channels that either belong to the same operator, or a different operator.
- Intersymbol interference (ISI) is the interference between successively transmitted symbols due to multipath propagation.
- Interchannel interference (ICI) is the interference on the same link between frequency channels that are simultaneously used to transmit parallel data streams on spatially separated multiple antennas
- Co-channel interference (CCI) is the interference that results from the reuse of the same radio-frequency channels at spatially separated locations

In general, different domains exist to achieve orthogonality, or quasiorthogonality, to allow multi-user access. In practice the following dimensions are used:

- frequency ⇒ frequency-division multiple access (FDMA)
- time ⇒ time-division multiple access (TDMA)
- space ⇒ space-division multiple access (SDMA)
- code ⇒ code-division multiple access (CDMA)

The particular multi-user access technology results in different levels of interference in the different interference categories mentioned before, depending on numerous factors such carrier frequency, propagation channel, mobility and deployment scenario. It is non-trivial to find the optimum multiuser access technique for a given scenario.

A further aspect in the design of a communication system is the spectral efficiency usually measured in bits per second, per Hertz, per square metre, [bits/second/Hz/m^2]. Regardless of the actual multiple access technology, the same radio-frequency resource has to be reused as often as possible in order to increase the spectral efficiency, but that inherently increases CCI which, in turn, reduces the system capacity, and the classical capacity trade-off in a cellular system is identified.

The cellular concept first introduced by (MacDonald, 1979) resulted in a systematic approach to control CCI. Due to its importance it will be explained in more detail in the following section.

1.3 The cellular concept

One of the key goals of mobile communication systems is to make services available *anywhere* and *anytime* which poses great challenges on the design of such systems. In particular, this requirement enforces the reuse of the limited radio-frequency spectrum. The reuse need to be organised such that CCI does not degrade the system performance below the guaranteed grade of service (GoS).

In conventional wireless systems a mobile entity is linked to a base station (BS). Base stations are connected to a radio network controller which uses additional interfaces that enable access to the public switched telephone network (PSTN). The principle structure of a cellular wireless system is shown in Figure 1.2. The transmitted signals experience a distance-dependent attenuation due to the wireless channel. Since the transmit powers are limited, the coverage area of a BS is also limited. The area covered by a BS is referred to as a cell. When modelling cellular systems, cells are approximated

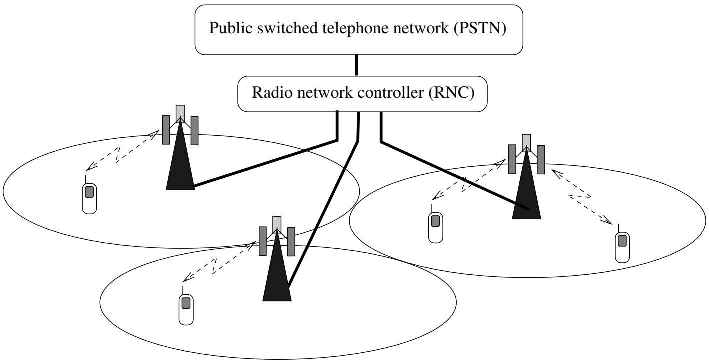

Fig. 1.2. A cellular wireless system.

by hexagons as they can be used to cover a plane without overlap (tessellation) and represent a good approximation of circles.

Since the total radio resource available is limited, the spatial dimension is used to allow wide area coverage. This is achieved by splitting the radio resource into groups. These groups are then assigned to different contiguous cells. This pattern is repeated as often as necessary until the entire area is covered. A single pattern is equivalent to a cluster. Therefore, a radio resource that is split into i groups directly corresponds to a cell cluster of size i. In this way it is ensured that the same radio resource is used only in cells that are separated by a defined minimum distance. This mechanism is depicted in Figure 1.3 (different groups of radio resource units is indicated by different shades of grey.). As a consequence the separation distance grows if the cluster size increases. Hence, increasing the cluster size acts in favour of low interference. However, an increased cluster size means that the same radio resource is used less often within a given area. As a result fewer users per unit area can be served. Therefore, there is a tradeoff between cluster size and capacity. One problem with the cellular concept is that it allows very little flexibility, and it is, for example, not straightforward to simply add new BSs. Due to this inflexibility the system is very often designed for worst-case interference scenarios. In most of the cases, however, this results in an inefficient use of the radio-frequency spectrum especially in the case of packet data services where there is no continuous transmission or where the transmission gaps might be exploited by other users. Hence, in an ideal scenario the total available radio resource would be used in every cell whilst the interference was kept at a tolerable level. Herein lies a potential advantage of CDMA over all other multiple access modes since the same frequency

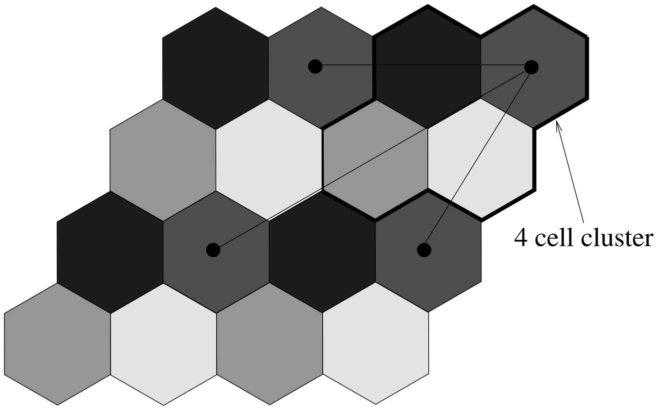

Fig. 1.3. The cellular concept.

carrier can be reused in every cell (Viterbi, 1995a) due to CDMA's inherent interference resistance. However, it has been shown that interference avoidance and interference mitigation techniques in combination with dynamic channel allocation and scheduling allow the full frequency reuse for other multiple access technologies, too. The cell capacity, finally, depends on many system functions such as power control, handover, scheduling, link adaptation etc. In the interest of high spectral efficiencies, the overall aim for next generation cellular systems is to avoid a fixed frequency reuse.

1.4 Modes of channel operation

There are three basic modes for operating a communication channel: simplex, half duplex and full duplex. The basic mechanisms are depicted in Figure 1.4. In the case of a simplex communication the information is

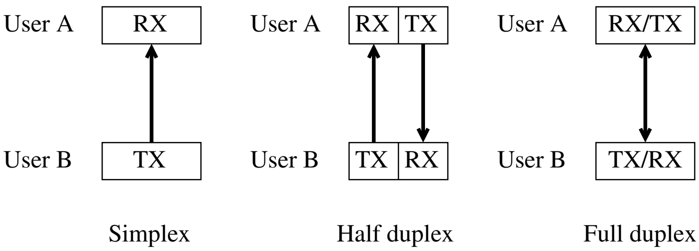

Fig. 1.4. Modes of channel operation.

passed from one entity to another without permitting any acknowledgement (one-way communication). Notable examples are television and radio broadcasting.

A half-duplex channel can send and receive, but not at the same time. This means one entity transmits at a time while the other entity listens, and vice versa. User A indicates when he/she wishes to terminate transmission giving the counterpart, user B in this case, the chance to talk. This leads to a 'pingpong' type of communication. This technique is used in talkback radio and CB (citizen band) radio where only one person can talk at a time. Note that access to the Internet merely requires a half duplex channel: consider user A sending a download request in principle, no further information needs to be transmitted and, thus, user A can go into the receive mode until all the required information is downloaded†.

In a full-duplex channel, information travels in both directions simultaneously. Two entities can receive and transmit at the same time. Telephony is an eminent example from this category.

In wireless communication systems two methods are used to achieve a full-duplex channel: time division duplex (TDD) and frequency division duplex (FDD). If the receive and transmit slots of a half-duplex channel are repeated periodically at short intervals, a full-duplex channel can be emulated by a half-duplex channel. This is exactly the mechanism used in TDD. In contrast, an FDD system separates both directions in the frequency domain so as to eliminate crosstalk. This means that the full-duplex channel is accomplished by two independent simplex channels. The basic mechanism of TDD and FDD are shown in Figure 1.5. In cellular communication the direction from the BS to the MS is referred to as the downlink‡. Similarly, the direction from the MS to the BS is the uplink.

The advantage of FDD is that it represents a true full-duplex channel which does not need any coordination between uplink and downlink transmission. The disadvantage is that two separated channels have to be maintained. Given that many new services do not require a full-duplex channel (predominately data applications as illustrated by an Internet session), FDD offers more features than would be required. In the case of a file download, for instance, the uplink channel is underused or even unused, which results in the waste of expensive radio resources. In comparison, the TDD technique does not represent a true full-duplex channel. It requires coordination

† In reality the protocols involved are more complex, but the basic principle remains the same.
‡ The terms 'downlink' and 'forward link' are synonymous. The terms 'forward link' is used primarily in the American literature. A similar dualism can be observed between 'uplink' and 'reverse link' and 'handover' and 'handoff', respectively.

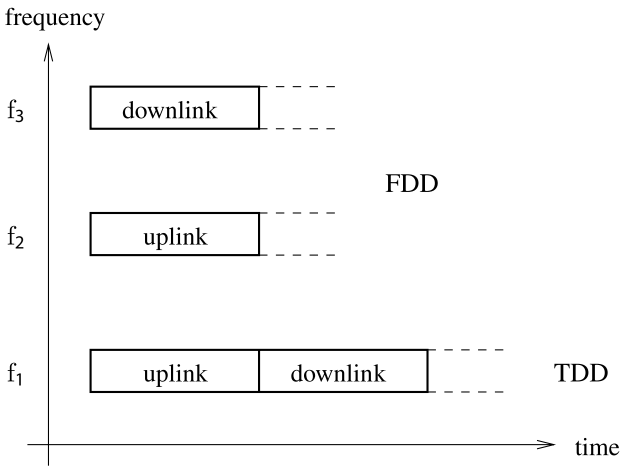

Fig. 1.5. The principles of TDD as compared with FDD.

(synchronisation), but due to its nature, it ideally supports services that basically only require an asymmetric half duplex channel. Given that future wireless communication is evolving towards the wireless Internet, the significance of TDD will grow.

1.5 Objectives of the book

One key objective of this book is to present an in-depth treatment of cellular TDD systems with a primary focus on TDD-CDMA systems, although consideration is also given to TDD-OFDM based systems. In this context, the book tries to answer the question whether the TDD technology can efficiently be used in cellular systems, and, if yes, under what conditions this can be achieved. It suggests algorithms that help to mitigate performance limitations due to TDD's inherent properties, and it shows techniques and algorithms that boost the advantages of TDD in such deployment scenarios.

The particular properties of TDD are considered to carry out interference and capacity analyses of cellular TDD-based systems. In this context, special emphasis is placed on the calculation of CCI and ACI for different cell layouts, power control algorithms, handover schemes and time slot (TS) synchronisation. As TS synchronisation is generally assumed to be critical to interference, particularly in a TDD system, the investigation of its impact on ACI and CCI is of utmost importance.