Access Methods

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Introduction

The radio channel is fundamentally a broadcast communication medium. Therefore, signals transmitted by one user can potentially be received by all other users within range of the transmitter. While this high connectivity is very useful in some applications, like broadcast radio or television, it requires stringent access control in wireless communication systems to avoid, or at least limit, interference between transmissions. Throughout, the term wireless communication systems is taken to mean communication systems which facilitate two-way communication between a portable radio communication terminal and the fixed network infrastructure. Such systems range from mobile cellular systems over personal communication systems (PCS) to cordless telephones.

The objective of wireless communication systems is to provide communication channels on demand between a portable radio station and a radio port or base station which connects the user to the fixed network infrastructure. Design criteria for such systems include **capacity**, cost of implementation, and quality of service. All of these measures are influenced by the method used for providing multiple-access capabilities. However, the opposite is also true: the access method should be chosen carefully in light of the relative importance of design criteria as well as the system characteristics.

Multiple access in wireless radio systems is based on insulating signals used in different connections from each other. The support of "parallel" transmissions on the up-link and down-link, respectively, is called multiple access, while the exchange of information in both directions of a connections is referred to as **duplexing**. Hence, multiple-access and duplexing are methods which facilitate the sharing of the broadcast communication medium. The necessary insulation is achieved by assigning to each transmission different components of the domains that contain the signals. The signal domains commonly used to provide multiple access capabilities include:

Spatial Domain All wireless communication systems exploit the fact that radio signals experience rapid attenuation during propagation. The propagation exponent ρ on typical radio channels lies between $\rho = 2$ and $\rho = 6$ with $\rho = 4$ a typical value. As signal strength decays inversely proportional to the ρ-th power of the distance far-away transmitters introduce interference which is negligible compared to the strength of the desired signal. The cellular design principle is based on the ability to re-use signals safely if a minimum re-use distance is maintained. Directional antennas can be used to enhance the insulation between signals. We will not focus further on the spatial domain in this treatment of access methods.

Frequency Domain Signals which occupy non-overlapping frequency bands can be easily separated using appropriate bandpass filters. Hence, signals can be transmitted simultaneously without interfering with each other. This method of providing multiple-access capabilities is called **frequency-division multiple-access (FDMA)**.

Time Domain Signals can be transmitted in non-overlapping time slots in a round-robin fashion. Thus, signals occupy the same frequency band but are easily separated based on their time of arrival. This multiple access method is called **time-division multiple-access (TDMA)**.

Code Domain In code-division multiple-access different users employ signals which have very small cross-correlation. Thus, correlators can be used to extract individual signals from a of signals even though they are transmitted simultaneously and in the same frequency band. The term **code-division multiple-access (CDMA)** is used to denote this form of channel sharing. Two forms of CDMA are most widely employed and will be described in detail below: frequency-hopping (FH) and direct-sequence (DS).

System designers have to decide in favor of one, or a combination, of the latter three domains to facilitate multiple-access. The three access methods are illustrated in Figure 1. The principal idea in all three of these access methods is to employ signals which are orthogonal or nearly orthogonal. Then, correlators which project the received signal into the subspace of the desired signal can be employed to extract a signal without interference from other transmissions.

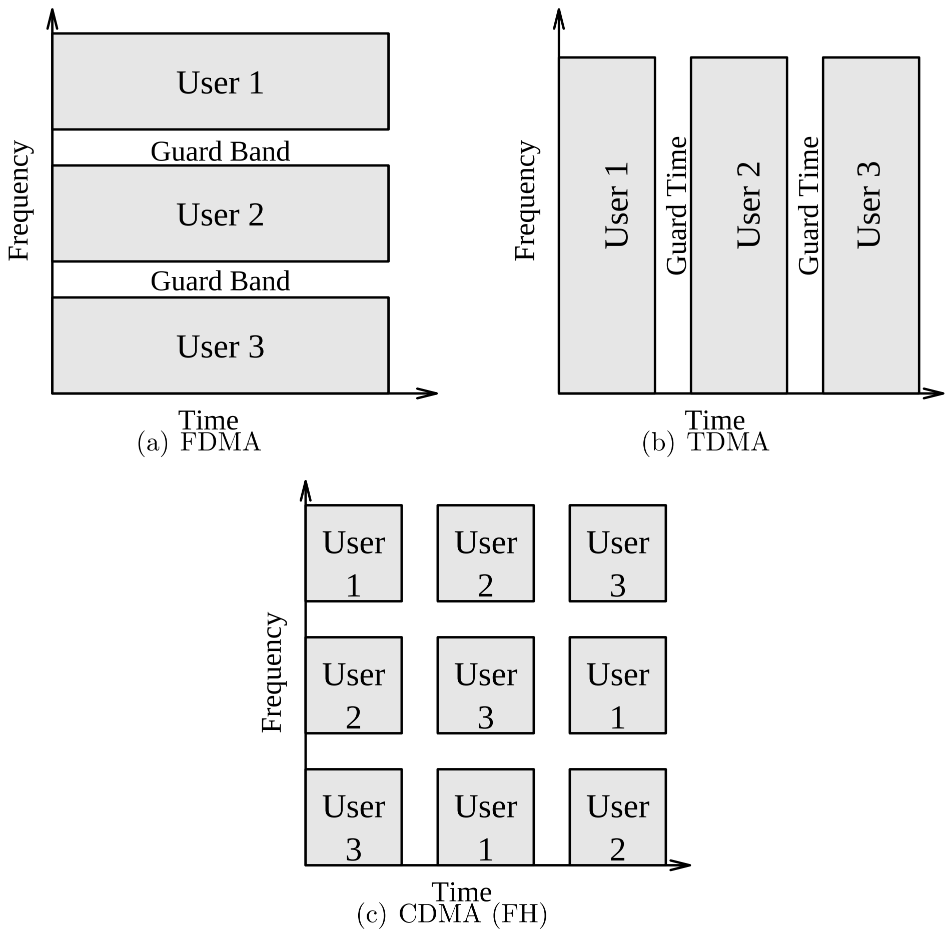

Figure 1: Multiple-access methods for wireless communication systems.

Preference for one access method over another depends largely on overall system characteristics as we will see in the sequel. No single access method is universally preferable and system considerations should be carefully weighed before the design decision is made. Before going into the detailed description of the different access methods, we will discuss briefly the salient features of some wireless communication systems. This will allow us later to assess the relative merits of the access methods in different scenarios.

Relevant Wireless Communication System Characteristics

Modern wireless radio systems range from relatively simple cordless telephones to mobile cellular systems and the emerging Personal Communication Systems (PCS). It is useful to consider such diverse systems as cordless telephone and mobile cellular radio to illustrate some of the fundamental characteristics of wireless communication systems [Cox, 1992].

Characteristic or Parameter	Cordless Telephone	Cellular Radio
Speech Quality	toll-quality	varying with channel quality; possibly decreased by speech pause exploitation
Transmission Range	<100 meter	100m – 30 km
Transmit Power	milliwatts	approx. 1 Watt
Base Station Antenna Height	approx. 1 m	tens of meters
Delay Spread	approx. 1 μsec	approx. 10 μsec
Complexity of Base Station	low	high
Complexity of User Set	low	high

Table 1: Summary of relevant characteristics of cordless telephone and cellular mobile radio.

A summary of the relevant parameters and characteristics for cordless telephone and cellular radio is given in Table 1. As evident from that table, the fundamental differences between the two systems are speech quality and the area covered by a base station. The high speech quality requirement in in the cordless application is the consequence of the availability of tethered access in the home and office and the resulting direct competition with wire-line telephone services. In the mobile cellular application the user has no alternative to the wireless access and may be satisfied with lower, but still acceptable, quality of service.

In cordless telephone applications the transmission range is short because the base station can simply be moved to a conveniently located wire-line access point (wall jack) to provide wireless network access where desired. In contrast, the mobile cellular base station must provide access for users throughout a large geographical area of up to approximately 30 km (20 miles) around the base station. This large coverage area is necessary to economically meet the promise of of uninterrupted service to roaming users.

The different range requirements directly affect the transmit power and antenna height for the two systems. High power transmitters used in mobile cellular user sets consume far more power than even complex signal processing hardware. Hence, sophisticated signal processing, including speech compression, voice activity detection, error correction and detection, and adaptive equalization, can be employed without substantial impact on the battery life in portable hand sets. Furthermore, such techniques are consistent with the goals of increased range and support of large numbers of users with a single, expensive base station. On the other hand, the high mobile cellular base station antennas introduce delay spreads which are one or two orders of magnitude larger than those commonly observed in cordless telephone applications.

Clearly, the two systems considered above are at extreme ends of the spectrum of wireless communications systems. Most notably, the emerging PCS systems fall somewhere between the two. However, the comparison above highlights some of the system characteristics which should be considered when discussing access methods for wireless communication systems.

Frequency Division Multiple Access

As mentioned above, in FDMA non-overlapping frequency bands are allocated to different users on a continuous time basis. Hence, signals assigned to different users are clearly orthogonal, at least ideally. In practice, out-of-band spectral components can not be completely suppressed leaving signals not quite orthogonal. This necessitates the introduction of guard bands between frequency bands to reduce adjacent channel interference, i.e., inference from signals transmitted in adjacent frequency bands (see also Figure 1(a)).

It is advantageous to combine FDMA with time-division duplexing (TDD) to avoid simultaneous reception and transmission which would require insulation between receive and transmit antennas. In this scenario, the base station and portable take turns using the same frequency band for transmission. Nevertheless, combining FDMA and frequency division duplex is possible in principle as is evident from the analog FM-based systems deployed throughout the world since the early 1980's.

Channel Considerations

In principle there exists the well known duality between TDMA and FDMA (see [Bertsekas and Gallager, 1987], p. 113 ff.). However, in the wireless environment propagation related factors have a strong influence on the comparison between FDMA and TDMA. Specifically, the duration of a transmitted symbol is much longer in FDMA than in TDMA. As an immediate consequence, an equalizer is typically not required in an FDMA based system because the delay spread is small compared to the symbol duration.

To illustrate this point, consider a hypothetical system which transmits information at a constant rate of 50 Kbit/s. This rate would be sufficient to support 32 Kbit/s ADPCM speech encoding, some coding for error protection, and control overhead. If we assume further that some form of QPSK modulation is employed the resulting symbol duration is 40 μsec. In relation to delay spreads of approximately 1 μsec in the cordless application and 10 μsec in cellular systems this duration is large enough that only little intersymbol interference is introduced. In other words, the channel is frequency non-selective, i.e., all spectral components of the signal are affected equally by the channel. In the cordless application an equalizer is certainly not required; cellular receivers may require equalizers capable of removing intersymbol interference between adjacent bits. Furthermore, it is well known that intersymbol interference between adjacent bits can be removed without loss in SNR by using Maximum-Likelihood Sequence Estimation (e.g. [Proakis, 1989], p. 622).

Hence, rather simple receivers can be employed in FDMA systems at these data rates. However, there is a flip-side to the above argument. Recall that the Doppler spread, which characterizes the rate at which the channel impulse response changes, is given approximately by $B_d = \frac{v}{c} f_c$, where v denotes the speed of the mobile user, c is the propagation speed of the electro-magnetic waves carrying the signal, and f_c is the carrier frequency. Thus for systems operating in the vicinity of 1 GHz, B_d will be less than 1 Hz in the cordless application and typically about 100 Hz for a mobile traveling on a highway. In either case, the signal bandwidth is much larger than the Doppler spread B_d and the channel can be characterized as slowly fading. While this allows tracking of the carrier phase and the use of coherent receivers it also means that fade durations are long in comparison to the symbol duration and can cause long sequences of bits to be subject to poor channel conditions. The problem is compounded by the fact that the channel is frequency non-selective because it implies that the entire signal is affected by a fade.

To overcome these problems either time diversity, frequency diversity, or spatial diversity could be employed. Time-diversity can be accomplished by a combination of coding and interleaving if the fading rate is sufficiently large. For very slowly fading channels, like in the cordless application, the necessary interleaving depth would introduce too much delay to be practical. Frequency diversity can be introduced simply by slow frequency hopping, a technique which prescribes user to change the carrier frequency periodically. Frequency hopping is a form of spectrum spreading because the bandwidth occupied by the resulting signal is much larger than the symbol rate. However, in contrast to direct sequence spread-spectrum discussed below the instantaneous bandwidth is not increased. The jumps between different frequency bands effectively emulate the movement of the portable and, thus, should be combined with the just described time-diversity methods. Spatial diversity is provided by the use of several receive or transmit antennas. At carrier frequencies exceeding 1 GHz antennas are small and two or more antennas can be accommodated even in the hand set. Furthermore, if FDMA is combined with time-division duplexing multiple antennas at the base station can provide diversity on both up-link and down-link. This is possible because the channels for the two links are virtually identical and the base station, using channel information gained from observing the portable's signal, can transmit signals at each antenna such that they combine coherently at the portable's antenna. Thus, signal processing complexity is moved to the base station extending the portable's battery life.

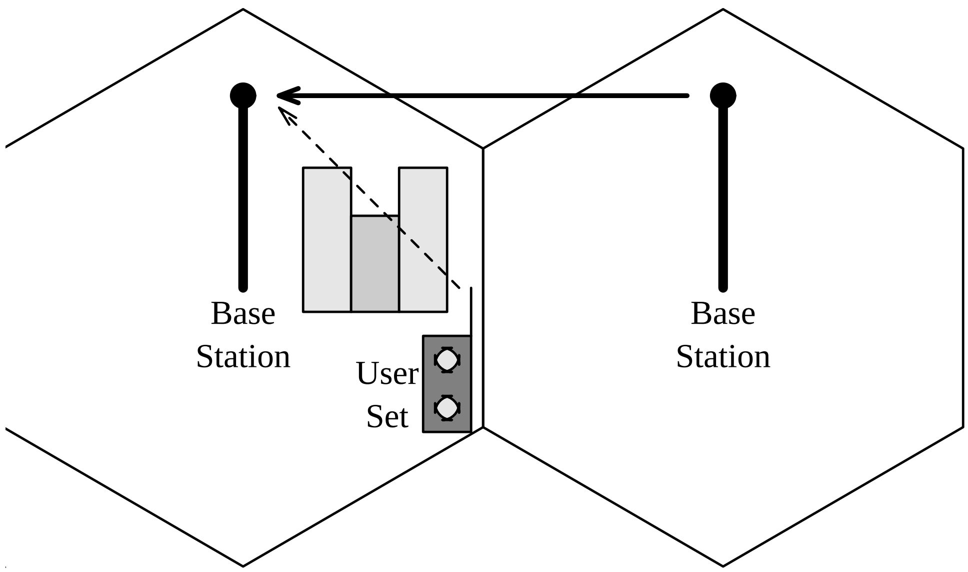

Figure 2: High base station antennas lead to stronger propagation paths between base stations than between a user set and the its base stations

Influence of Antenna Height

In the cellular mobile environment base station antennas are raised considerably to increase the coverage area. Antennas mounted on towers and rooftops are a common sight and antenna heights of 50 meters above ground are no exceptions. Besides increasing the coverage area, this has the additional effect that frequently there exists a better propagation path between two base station antennas than between a mobile and the base station (see Figure 2).

Assuming that FDMA is used in conjunction with TDD as motivated above, then base stations and mobiles transmit on the same frequency. Now, unless there is tight synchronization between all base stations, signals from other base stations will interfere with the reception of signals from portables at the base station. To keep the interference at acceptable levels it is necessary to increase the re-use distance, i.e., the distance between cells using the same frequencies. In other words, sufficient insulation in the spatial domain must be provided to facilitate the separation of signals. Notice, that these comments apply equally to co-channel and adjacent channel interference.

This problem does not arise in cordless applications. Base station antennas are generally of the same height as user sets. Hence, interference created by base stations is subject to the same propagation conditions as signals from user sets. Furthermore, in cordless telephone applications there are frequently attenuating obstacles, like walls, between base stations which reduce intra-cell interference further. Notice that this reduction is vital for the proper functioning of cordless telephones as there is typically no network planning associated with installing a cordless telephone. As a safety feature, to overcome intra-cell interference, adaptive channel management strategies, based on sensing interference levels, can be employed.

Example: CT2

The CT2 standard was originally adopted in 1987 in Great Britain and improved with a common air interface (CAI) in 1987. The CAI facilitates interoperability between equipment from different vendors while the original standard only guarantees non-interference. The CT2 standard is used in home and office cordless telephone equipment and has been used for telepoint applications [Goodman, 1991b].

CT2 operates in the frequency band 864–868 MHz and uses carriers spaced at 100 KHz. FDMA with time division duplexing is employed. The combined gross bit rate is 72 Kbit/s, transmitted in frames of 2 ms duration of which the first half carries down-link and the second half carries up-link information. This set-up supports a net bit rate of 32 Kbit/s of user data (32 Kbit/s ADPCM encoded speech) and 2 Kbit/s control information in each direction. The CT2 modulation technique is binary frequency shift keying.

Further Remarks

From the discussion above it is obvious that FDMA is a good candidate for applications like cordless telephone. In particular the simple signal processing make it a good choice for inexpensive implementation in the benign cordless environment. The possibility to concentrate signal processing functions in the base station strengthens this aspect.

In the cellular application, on the other hand, FDMA is inappropriate because of the lack of “built-in” diversity, and the potential for severe intra-cell interference between base stations. A further complication arises from the difficulty of performing hand-overs if base-stations are not tightly synchronized.

For PCS the decision is not as obvious. Depending on whether the envisioned PCS application resembles more a cordless PBX than a cellular system FDMA may be an appropriate choice. We will see below that it is probably better to opt for a combined TDMA/FDMA or a CDMA based system to avoid the pitfalls of pure FDMA systems and still achieve moderate equipment complexities.

Finally, there is the problem of channel assignment. Clearly, it is not reasonable to assign a unique frequency to each user as there are not sufficiently many frequencies and the spectral resource would be unused whenever the user is idle. Instead, methods which allocate channels on demand can make much more efficient use of the spectrum. Such methods will be discussed further during the description of TDMA systems.

Time Division Multiple Access

In TDMA systems users share the same frequency band by accessing the channel in non-overlapping time intervals in a round robin fashion [Falconer, Adachi, and Gudmundson, 1995]. Since the signals do not overlap they are clearly orthogonal and the signal of interest is easily extracted by switching the receiver on only during the transmission of the desired signal. Hence, the receiver "filters" are simply windows instead of the bandpass filters required in FDMA. As a consequence, the guard time between transmissions can be made as small as the synchronization of the network permits. Guard times of 30-50 μs between time slots are commonly used in TDMA based systems. As a consequence, all users must be synchronized with the base station to within a fraction of the guard time which is achievable by distributing a master clock signal on one of the base station's broadcast channels.

TDMA can be combined with time-division duplexing (TDD) or frequency-division duplexing (FDD). The former duplexing scheme is used for example in the Digital European Cordless Telephone (DECT) standard and is well suited for systems in which base-to-base and mobile-to-base propagation paths are similar, i.e., systems without extremely high base station antennas. Since both the portable and the base station transmit on the same frequency, some signal processing functions for the down-link can be implemented in the base station, as discussed above for FDMA/TDD systems.

In the cellular application the high base station antennas make FDD the more appropriate choice. In these systems, separate frequency bands are provided for up-link and down-link communication. Notice, that it is still possible and advisable to stagger the up-link and down-link transmission intervals such that they don't overlap to avoid that the portable must transmit and receive at the same time. With FDD the up-link and down-link channel are not identical and hence signal processing functions can not be implemented in the base-station; antenna diversity and equalization have to be realized in the portable.

Propagation Considerations

In comparison to a FDMA system supporting the same user data rate the transmitted data rate in a TDMA system is larger by a factor equal to the number of users sharing the frequency band. This factor is eight in the pan-European GSM systems and three in the D-AMPS system. Thus, the symbol rate is reduced by the same factor and severe intersymbol interference results, at least in the cellular environment.

To illustrate, consider the example from above where each user transmits 25 K symbols per second. Assuming eight user per frequency band leads to a symbol duration of 5 μsec. Even in the cordless application with delay spreads of up to 1 μsec, an equalizer may be useful to combat the resulting interference between adjacent symbols. In cellular systems, however, the delay spread of up to 20 μsec introduces severe intersymbol interference spanning up to 5 symbol periods. As the delay spread often exceeds the symbol duration the channel can be classified as frequency selective, emphasizing the observation that the channel affects different spectral components differently.

The intersymbol interference in cellular TDMA systems can be so severe that linear equalizers are insufficient to overcome its negative effects. Instead more powerful, non-linear decision feedback or maximum-likelihood sequence estimation equalizers must be employed [Proakis, 1991]. Furthermore, all these equalizers require some information about the channel impulse response which must be estimated from the received signal by means of an embedded training sequence. Clearly, the training sequence carries no user data and, thus, wastes valuable bandwidth.

In general, receivers for cellular TDMA systems will be fairly complex. On the positive side of the argument, however, the frequency selective nature of the channel provides some "built-in" diversity which makes transmission more robust to channel fading. The diversity stems from the fact that the multi-path components of the received signal can be resolved at a resolution roughly equal to the symbol duration and the different multi-path components can be combined by the equalizer during the demodulation of the signal. To further improve robustness to channel fading coding and interleaving, slow frequency hopping, and antenna diversity can be employed as discussed in connection with FDMA.

Initial Channel Assignment

In both FDMA and TDMA systems, channels should not be assigned to a mobile on a permanent basis. A fixed assignment strategy would either be extremely wasteful of precious bandwidth or highly susceptible to co-channel interference. Instead channels must be assigned on demand. Clearly, this implies the existence of a separate up-link channel on which mobiles can notify the base station of their need for a traffic channel. This up-link channel is referred to as the **random-access channel** because of the type of strategy used to regulate access to it.

The successful procedure for establishing a call that originates from the mobile station is outlined in Figure 3. The mobile initiates the procedure by transmitting a request on the random access channel. Since this channel is shared by all users in range of the base station a random access protocol, like the ALOHA protocol, has to be employed to resolve possible collisions. Once the base station has received the mobile's request it responds with an immediate assignment message which directs the mobile to tune to a dedicated control channel for the ensuing call setup. Upon completion of the call setup negotiation a traffic channel, i.e., a frequency in FDMA systems or a time slot in TDMA systems, is assigned by the base station and all future communication takes place on that channel. In the case of a mobile-terminating call request, the above sequence of events is preceded by a paging

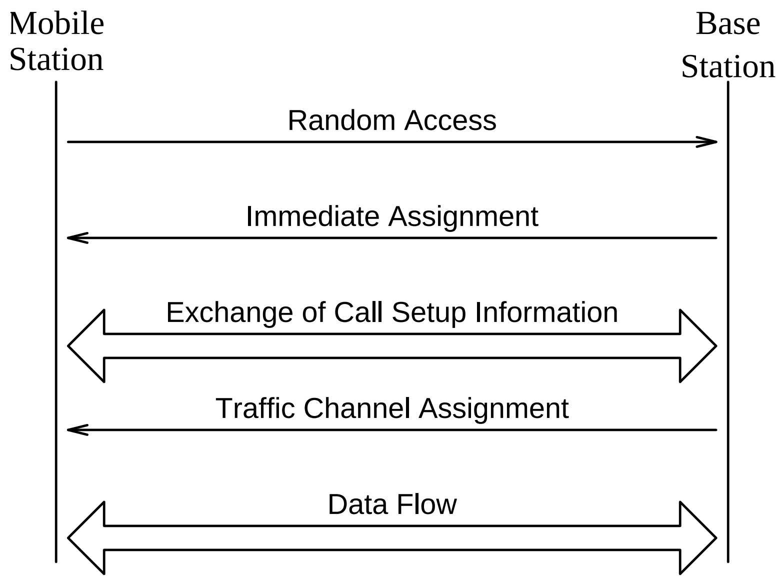

Figure 3: Mobile-originating call establishment

message alerting the mobile of the call request.

Example: GSM

Named after the organization that created the system standards (Groupe Speciale Mobile) this pan-European digital cellular system has been deployed in Europe since the early 1990s [Hodges, 1990]. GSM uses combined TDMA and FDMA with frequency-division duplex for access. Carriers are spaced at 200 KHz and support eight TDMA time slots each. For the up-link the frequency band 890–915 MHz is allocated, while the down-link uses the band 935–960 MHz. Each time slot is of duration 577 μs which corresponds to 156.26 bit periods, including a guard time of 8.25 bit periods. Eight consecutive time slots form a GSM frame of duration 4.62 ms.

The GSM modulation is Gaussian minimum shift keying with time-bandwidth product of 0.3, i.e., the modulator bandpass has a cut-off frequency of 0.3 times the bit rate. At the bit rate of 270.8 Kbit/s, severe intersymbol interference arises in the cellular environment. To facilitate coherent detection, a 26 bit training sequence is embedded into every time slot. Time diversity is achieved by interleaving over eight frames for speech signals and 20 frames for data communication. Sophisticated error correction coding with varying levels of protection for different outputs of the speech coder is provided. Note that the round-trip delay introduced by the interleaver is on the order of 80 ms for speech signals. GSM provides slow frequency hopping as a further mechanism to improve the efficiency of the interleaver.

Further Remarks

In cellular systems, like GSM or the north-American D-AMPS, TDMA is combined with FDMA. Different frequencies are used in neighboring cells to provide orthogonal signaling without the need for tight synchronization of base stations. Furthermore, channel assignment can then be performed in each cell individually. Within a cell one or more frequencies are shared by users in the time domain.

From an implementation standpoint TDMA systems have the advantage that common radio and signal processing equipment at the base station can be shared by users communicating on the same frequency. A somewhat more subtle advantage of TDMA systems arises from the possibility to monitor surrounding base stations and frequencies for signal quality to support mobile assisted handovers.

Code Division Multiple Access

CDMA systems employ wide-band signals with good cross-correlation properties [Kohno, Meidan, and Milstein, 1995]. That means, the output of a filter matched to one user's signal is small when a different user's signal is input. A large body of work exists on spreading sequences which lead to signal sets with small cross-correlations [Sarwate and Pursley, 1980]. Because of their noise-like appearance such sequences are often referred to as pseudo-noise (PN) sequences and because of their wide-band nature CDMA systems are often called spread-spectrum systems.

Spectrum spreading can be achieved mainly in two ways: through frequency hopping as explained above or through direct sequence spreading. In direct sequence spread spectrum a high-rate, antipodal pseudo-random spreading sequence modulates the transmitted signal such that the bandwidth of the resulting signal is roughly equal to the rate of the spreading sequence. The cross-correlation of the signals is then largely determined by the cross-correlation properties of the spreading signals. Clearly, CDMA signals overlap in both time and frequency domain but are separable based on their spreading waveforms.

An immediate consequence of this observation is that CDMA systems do not require tight synchronization like TDMA systems. By the same token, frequency planning and management are not required as frequencies are re-used throughout the coverage area.

Propagation Considerations

Spread spectrum is well suited for wireless communication systems because of its "built-in" frequency diversity. As discussed before, in cellular systems the delay spread measures several microseconds and, hence, the coherence bandwidth of the channel is smaller than 1 MHz. Spreading rates can be chosen to exceed the coherence bandwidth such that the channel becomes frequency selective, i.e., different spectral components are affect in unequally by the channel and only parts of the signal are affected by fades. Expressing the same observation in time domain terms, multi-path components are resolvable at a resolution equal to the chip period and can be combined coherently for example by means of a RAKE receiver [Proakis, 1989]. An estimate of the channel impulse response is required for the coherent combination of multi-path components. This estimate can be gained from a training sequence or by means of a so-called "pilot" signal.

Even for cordless telephone systems, operating in environments with sub-microsecond delay spread and corresponding coherence bandwidths of a few MHz, the spreading rate can be chosen large enough to facilitate multi-path diversity. If the combination of multi-path components described above is deemed to complex a simpler, but less powerful, form of diversity can be used which decorrelates only the strongest received multi-path component and relies on the suppression of other path components by the matched filter.

Multiple-Access Interference

If it is possible to control the relative timing of the transmitted signals, like on the down-link, the transmitted signals can be made perfectly orthogonal and, if the channel only adds white Gaussian noise, matched filter receivers are optimal for extracting a signal from the superposition of waveforms. If the channel is dispersive because of multi-path the signals arriving at the receiver will be no longer orthogonal and will introduce some multiple-access interference, i.e., signal components from other signals which are not rejected by the matched filter.

On the up-link extremely tight synchronization to within a fraction of a chip period, which is defined as the inverse of the spreading rate, is generally not possible and measures to control the impact of multiple-access interference must be taken. Otherwise, the near-far problem, i.e., the problem of very strong undesired users' signals overwhelming the weaker signal of the desired user, can severely decrease performance. Two approaches are proposed to overcome the near-far problem: power control with soft handovers and multi-user detection.

Power control attempts to ensure that signals from all mobiles in a cell arrive at the base station with approximately equal power levels. To be effective power control must be accurate to within about 1 dB and fast enough to compensate for channel fading. For a mobile moving at 55 mph and transmitting at 1 GHz, the Doppler bandwidth is approximately 100 Hz. Hence, the channel changes its characteristic drastically about 100 times per second and on the order of 1000 bit/s must be sent from base station to mobile for power control purposes. As different mobiles may be subject to vastly different fading and shadowing conditions a large dynamic range of about 80 dB must be covered by power control. Notice, that power control on the down-link is really only necessary for mobiles which are about equidistant from two base stations, and even then neither the update rate nor the dynamic range of the up-link is required.

The interference problem that arises at the cell boundaries where mobiles are within range of two or more base stations can be turned into an advantage through the idea of soft handover. On the down-link, all base stations within range can transmit to the mobile which in turn can combine the received signals to achieve some gain from the antenna diversity. On the up-link a similar effect can be obtained by selecting the strongest received signal from all base stations which received a user's signal. The base station which receives the strongest signal will also issue power control commands to minimize the transmit power of the mobile. Note, however, that soft handover requires fairly tight synchronization between base stations and one of the advantages of CDMA over TDMA is lost.

Multi-user detection is still an emerging technique. It is probably best used in conjunction with power control. The fundamental idea behind this technique is to model multiple-access interference explicitly and devise receivers which reject or cancel the undesired signals. A variety of techniques have been proposed ranging from optimum maximum-likelihood sequence estimation via multi-stage schemes, reminiscent of decision feedback algorithms, to linear decorrelating receivers. An excellent survey of the theory and practice of multi-user detection was given by Verdu [Verdu, 1992].

Further Remarks

CDMA systems work well in conjunction with frequency division duplexing. This arrangement decouples the power control problem on the up-link and down-link, respectively.

Signal quality enhancing methods like time diversity through coding and interleaving can be applied just like with the other access methods. In spread spectrum systems, however, coding can be "built" in to the spreading process avoiding the loss of bandwidth associated with error protection. Additionally, CDMA lends itself naturally to the exploitation of speech pauses which make up more than half the time of a connection. If no signals are transmitted during such pauses then the instantaneous interference level is reduced and the total number of users supportable by the system can be approximately doubled.

Comparison and Outlook

The question which of the access methods is best does not have a single answer. Based on the discussion above FDMA is only suited for applications like cordless telephone with very small cells and sub-microsecond delay spreads. In cellular systems and for most visions of personal communication systems the choice reduces to TDMA versus CDMA.

In terms of complexity, TDMA receivers require adaptive, nonlinear equalizers when operating in environments with large delay spreads. CDMA systems, in turn, need RAKE receivers and sophisticated power control algorithms. In the future, some form of multiple-access interference rejection is likely to be implemented as well. Time synchronization is required in both systems albeit for different reasons. The additional complexity for coding and interleaving is comparable for both access methods.

An often quoted advantage of CDMA systems is the fact that the performance will degrade gracefully as the load increases. In TDMA systems, in turn, requests will have to be blocked once all channels in a cell are in use. Hence, there is a hard limit on the number of channels per cell. However, there are proposals for extended TDMA systems which incorporate re-assignment of channels during speech pauses. Not only would such extended TDMA systems match the advantage of CDMA systems from the exploitation of speech pauses but they would also lead to a soft limit on the system capacity. The extended TDMA proposals would implement the statistical multiplexing of the user data by means of the Packet Reservation Multiple Access protocol [Goodman, 1991a]. The increase in capacity depends on the acceptable packet loss rate; in other words, small increases in the load lead to small increases in the packet loss probability.

Many comparisons in terms of capacity between TDMA and CDMA can be found in the recent literature. However, such comparisons are often invalidated by making assumptions which favor one access method over the other. An important exception constitutes the recent paper by Wyner [Wyner, 1994]. Under a simplified model which still captures the essence of cellular systems he computes the Shannon capacity. Highlights of his results include:

- TDMA is distinctly suboptimal in cellular systems.
- When the signal-to-noise-ratio is large CDMA appears to achieve twice the capacity of TDMA.
- Multi-user detectors are essential to realize near-optimum performance in CDMA sys-

tems.

- Intra-cell interference in CDMA systems has a detrimental effect when the signal to noise ratio is large, but it can be exploited via diversity combining to increase capacity when the signal to noise ratio is small.

More research along this avenue is necessary to confirm the validity of the results. In particular, incorporation of realistic channel models into the analysis is required. However, this work represents a substantial step towards quantifying capacity increases achievable with CDMA.

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Defining Terms

Capacity While Shannon originally defined capacity as the maximum data rate which permits error-free communication in a given environment, a looser interpretation is normally employed in wireless communication systems. Here capacity denotes the traffic density supported by the system under consideration normalized with respect to bandwidth and coverage area.

Multiple Access denotes the support of simultaneous transmissions over a shared communication channel.

Duplexing refers to the exchange of messages in both directions of a connection.

FDMA In frequency-division multiple-access simultaneous access to the radio channel is facilitated by assigning non-overlapping frequency bands to different users.

TDMA Time-division multiple-access systems assign non-overlapping time-slots to different users in a round-robin fashion.

CDMA Code-division multiple-access systems use signals with very small cross-correlations to facilitate sharing of the broadcast radio channel. Correlators are used to extract the desired user's signal while simultaneously suppressing interfering, "parallel" transmissions.

Random-Access Channel This up-link control channel is used by mobiles to request assignment of a traffic channel. A random access protocol is employed to arbitrate access to this channel.

For Further Information

Several of the IEEE publications, including the Transactions on Communications, Journal on Selected Areas in Communications, Transactions on Vehicular Technology, Communications Magazine, and Personal Communications contain articles the on subject of access methods on a regular basis.