MOSE - A Simulation Environment for Mobile Communications Systems

Fredrik Gunnarsson, Jonas Blom and Fredrik Gustafsson

Department of Electrical Engineering
Linköpings universitet, SE-581 83 Linköping, Sweden
WWW: http://www.control.isy.liu.se
Email: {fred, jb, fredrik}@isy.liu.se

November 30, 1998

Report no.: LiTH-ISY-R-2033
Submitted to (Nothing)

Abstract

Thorough analytical analysis of cellular radio networks is difficult in general. Therefore simulation environments are adequate tools to gain understanding about the behaviour of algorithms used in cellular radio networks. In this report MOSE (MObile communications System Emulator) is described. The objective has been to develop an intuitive and user-friendly environment supported by a graphical user-interface. The implemented models include time-varying communication channels, co-channel interference, time delays and constraints. Several filtering and power control algorithms are implemented, and dedicated tests facilitate comparison with respect to different aspects.

Keywords: Cellular radio systems; Simulations; Fading; Propagation modeling; Power control; Time delays; Constraints.

Contents

Chapter 1

Introduction

Thorough analytical analysis of cellular radio networks is difficult in general. Often one has to rely on coarse models describing simple cases. When considering more realistic cases, we have to employ more complex models. Therefore simulation environments are adequate tools to gain understanding about the behavior of algorithms used in cellular radio networks. In this report MOSE (MObile communications System Emulator) is described. The objective has been to develop an intuitive and user-friendly environment supported by a graphical user-interface.

1.1 Outline

After this introduction, the scope of Chapter 2 is to review models used to describe the operation of a cellular radio system. In the same time the chapter will serve as a tutorial in basic radio communication issues relevant for cellular networks. Furthermore, the objective with MOSE will be described together with its focus and delimitations.

The aim of MOSE is slightly shifted towards issues related to power control in such networks. In Chapter 3, we therefore bring up a few in our opinion important aspects of power control. In addition, the algorithms implemented in MOSE are described and discussed briefly. For a more thorough discussion, we refer to [1].

The simulation environment should be fairly intuitive and user-friendly. However, some examples are given in Chapter 4 in order to illuminate some basic features. Finally some motivations of the implementation are given in Appendix A, and in Appendix B a somewhat complete reference to the functionality of MOSE is found.

1.2 Implementation

MOSE is implemented in MATLAB™ 5 and requires Statistics Toolbox and Signal Processing Toolbox. It is platform independent and is available at

```
>> addpath('\home\rt\fred\Projekt\Ericsson\Matlab\MOSE_2.1');
```

Chapter 2

Mobile Communications Systems

In this chapter we will briefly describe mobile communications systems. The objective is to cover the main issues so that a reader without prior knowledge will understand the problems and challenges in such systems. In the presentation we also introduce the terminology used in the field.

There are several books covering the development of mobile communications systems. We cite books by Ahlin and Zander [2], Garrard [3], Jakes [4], Lee [5], Rappaport [6], Steele [7] and Stüber [8].

2.1 Radio Communication

The purpose of a radio communication system is to transmit a message from a source to a user. These systems can be classified in a number of ways, but here it is natural to treat analog and digital systems separately. However, all radio communication systems are using the same medium - the radio channel. The transmitted signal is affected by radio propagation effects, thermal noise, interfering signals and other types of disturbances. For further details on radio communication, we refer to [2, 9, 8].

An analog communication system consists of a *transmitter*, a *radio channel* and a *receiver*. In the transmitter, the message signal is filtered and modulated onto the carrier signal. It is then transmitted over the radio channel and demodulated in the receiver. The cellular systems of the first generation are analog and use Frequency Modulation (FM).

The basic elements of a digital communication system are illustrated in Figure 2.1. It still consists of a transmitter and a receiver communicating over a radio channel, but the internal components are a bit more sophisticated. Initially the message is converted into a sequence of bits by the *source encoder*. In order to enable a more reliable transmission, redundancy is added in a controlled manner by the *channel encoder*. This redundancy in the bit sequence aids the receiver in decoding the desired sequence. It can be used both for error detection and error correction and is important to obtain good performance in a digital system, due to the disturbances introduced by the channel.

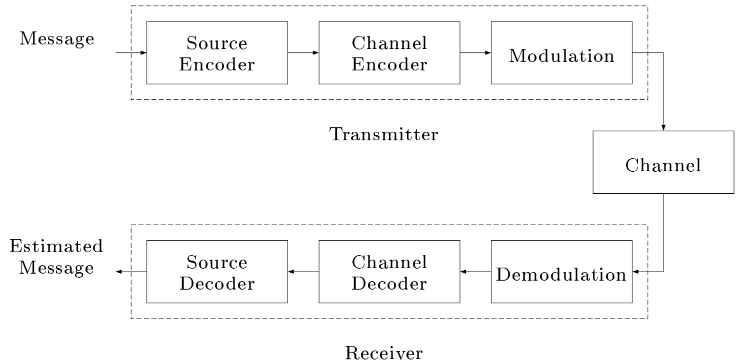

Figure 2.1: Block diagram of a digital communication system.

The radio channel is in practice a channel for continuous signals, and therefore the bit sequence has to be *modulated* onto an analog carrier signal. The primary objective is to utilize the available bandwidth efficiently, while achieving a prescribed performance, given by the number of erroneous bits received divided by the number of bits transmitted. This is referred to as the *Bit Error Rate* (BER). Note that the BER is primarily affected by the radio channel and the modulation scheme used. Among the systems of the second generation, GSM and PDC are using Gaussian Minimum Shift Keying (GMSK) and D-AMPS and IS-95 are using $\pi/4$-shift Quaternary Phase Shift Keying ($\pi/4$-QPSK).

At the receiver, the signal is processed in the reversed order compared to the transmitter, with the objective to reconstruct the original message. The *demodulator* will convert the corrupted waveform to an estimate of the transmitted bit sequence, from which the *channel decoder* reconstructs the data stream by using the redundancy in the transmitted bit sequence. Finally the *source decoder* tries to reconstruct the original message signal.

2.2 Radio Wave Propagation

The Maxwell equations provide, at least in principle, solutions to all problems regarding electromagnetic fields. If all facts were known, we could in theory determine the effects on a radio wave when it propagates through a medium. However, these solutions tend to be far too complex to provide understanding of problems in practical situations. Instead, simple models may be used to capture the physical phenomenons coarsely, in order to provide an intuitive understanding of real-life cases.

It is very hard to come up with simple models that are valid for all frequencies, but since the issue here is mobile communications systems, we can focus on a limited frequency band. The presented mobile communications systems are using the UHF band (300 - 3000 MHz), which has well suited properties for wireless communication. In this band it is possible to use signals with relatively large bandwidth, which gives higher data transmission capacity. The effects of rain and moisture are slight, but the radio waves are shielded and reflected by mountains and buildings.

We are interested in the power gain[1] $\bar{g}$ of the received signals, that is if a transmitter emits a signal using the power $\bar{p}$ the receiver will observe a signal power of $\bar{g}\bar{p}$. In order to model this gain we separate the propagation effects in three groups and use the model

$$\bar{g} = \bar{g}_p \bar{g}_s \bar{g}_m.$$

The distance dependent attenuation is modeled by the path loss ($\bar{g}_p$). Terrain variations are resulting in shielding and diffraction and is modeled by the shadow fading ($\bar{g}_s$), while the effects of the reflections are captured by the multipath fading ($\bar{g}_m$). These models are further explored below. For more extensive material regarding radio wave propagation, see [8].

It will be important to note the difference between $\bar{g}$, which represents the power gain in linear scale, and g which is the power gain in dB.

2.2.1 Path Loss

On a long time average, the observed power at the receiver depends mainly on the distance to the transmitter. One of the simplest models is based on the assumption of propagation in free space, but except for satellite communication applications, this is too coarse. When we consider propagation over plane earth an approximation of the path loss is derived in [4], and given by

$$\bar{g}_p = \frac{C_p}{r^\alpha}, \tag{2.1}$$

where r is the distance between the transmitter and the receiver, the *path loss exponent* α is a constant equal to 4, and C_p is a constant which depends on antenna specific parameters and the transmitted wavelength.

Empirical studies by Okumura [10] and Hata [11] resulted in path loss models for urban, suburban and rural areas. Equation (2.1) still holds for the long time average gain if we note that the constants C_p and α depend on the type of terrain. Typical values of α are about $2-5$, where the lowest value corresponds to free space propagation, and the higher to urban environments with high buildings. Note that the plane earth approximation is covered by this range in α.

2.2.2 Shadow fading

As mentioned above, the long time average is given by the path loss. Terrain variations will however result in diffraction and shielding phenomenons, which manifest themselves as a slow variation in this average gain over a distance corresponding to several tens of wavelengths. This effect is referred to as *shadow fading*. Okumura [10] and Hata [11] were pioneers in studying these variations. They used values in dB and argued that the shadow fading can be modeled using a zero-mean Gaussian random variable, i.e.

$$g_s \sim N(0, \sigma_s). \tag{2.2}$$

[1] Often the term *attenuation* is used to stress the fact that the gain is less than one.

Hence the linear shadow fading gain ($\bar{g}_s$) can be modeled using a log-normal distribution, i.e. the corresponding value in dB is normal distributed with zero-mean and variance σ_s^2. This model is reasonably accurate when discussing separate samples of the gain, but it is not sufficient if we consider a receiver that is moving around in the terrain. The effects from the terrain are correlated and if the receiver is shielded at one instant, it will most likely be shielded for some time thereafter.

To include this spatial correlation, Gudmundson [12] proposed a first order filter, that incorporates the velocity of the mobile v and relates it to a correlation distance d. In essence, the proposal breaks down to

$$g_s(t+T_s) = a(t)g_s(t) + \eta(t),$$

where $a(t)$ is a parameter (possibly time-varying), T_s is the sample interval, and $\eta(t) \sim N(0, \sigma_s')$. In order to capture the velocity dependency, Gudmundson proposes

$$a(t) = \epsilon_d^{v(t)T_s/d},$$

where ϵ_d is the correlation between two points separated by the distance d, and $v(t)$ is the velocity of the mobile station. A more practical approach is to state that a correlation less than or equal to e^{-1} is no correlation. Then the parameter d denotes the least distance between two uncorrelated points. Hence

$$g_s(t+T_s) = e^{-v(t)T_s/d} g_s(t) + \eta(t).$$

Moreover, for intuitive parameterization, it is desirable to have $\mathrm{E}\{g_s^2(t)\} = \sigma_s^2$ just as in (2.2). This is met by

$$\sigma_s' = \sigma_s \sqrt{1 - e^{-2v(t)T_s/d}}$$

2.2.3 Multipath fading

In the presence of several large objects, there will be a great number of reflected signals that reach the receiver. Depending on their phase they interfere either constructively or destructively resulting in *multipath fading*. For digital systems it is important to determine if this fading can be assumed to be constant for each received symbol. If that is the case, the fading is referred to as *flat*, but if not, we are experiencing *intersymbol interference* due to this *frequency selective* fading. For low to moderate data rates the intersymbol interference can be counteracted using *channel equalization* [8] and therefore it is common to model the multipath fading as flat.

Just as in the case of shadow fading, the multipath fading has a spatial correlation as exemplified in Figure 2.2. Thus the fading is depending on the velocity of the mobile station. One may also draw the erroneous conclusion, that the fading is constant if the location of the mobile station is fixed. The truth is that the environment is also moving, and it is the movement relative to the environment that matters. Since the origin of the multipath fading is different path lengths of the reflected waves, it is also depending on the wavelength of the signal. Therefore we will also observe a correlation in the frequency domain, see Figure 2.2.

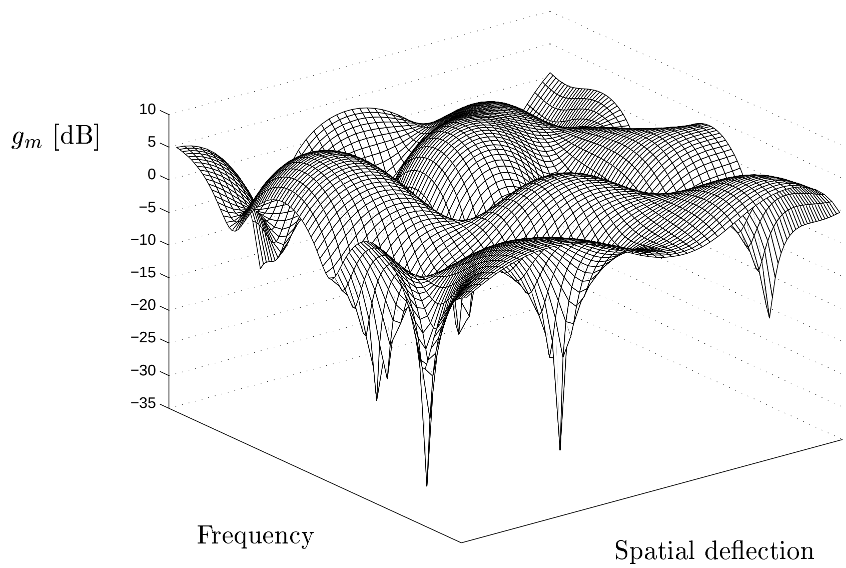

Figure 2.2: A realization of the multipath fading as a function of spatial deflection and frequency.

2.2.4 Example: Spatially Correlated Propagation

In Figure 2.3 we see a sample of how the power gain may vary when a mobile station is moving in the terrain. It is assumed that the distance to the transmitter is almost constant and that no Line-of-Sight (LoS)component reaches the receiver. Therefore the variations are due to shadow and Rayleigh fading [13] with spatial correlation.

2.2.5 Time Frame Influence

It is important to relate the expected variations of the power gain to the sample interval. For instance in GSM, measurements are available at a frequency of only 2 Hz, i.e. the sample interval $T_s = 0.5$s. Therefore the effects of multipath will be averaged out, and thus not seen in the measurements. Consequently, we cannot expect to be able to mitigate multipath by only controlling the transmitter powers in this case. This is the reason why only path loss and shadow fading are modeled in MOSE.

2.3 Multi-User Communications

Consider a case of one base station (BS) serving a certain service area. The BS transmits and receives data to and from the M mobile stations (MS) in the service area. The communication goes in two directions, and one distinguishes between the downlink (forward) channels from BS to MS, and the uplink (reverse) channels from MS to BS. For simplicity we focus on the downlink from BS to MS number 1. Assume that the BS is transmitting the signals $s_1(t), s_2(t), \dots, s_M(t)$ to the MS's. Figure 2.4 provides a simple model of the situation at the receiver

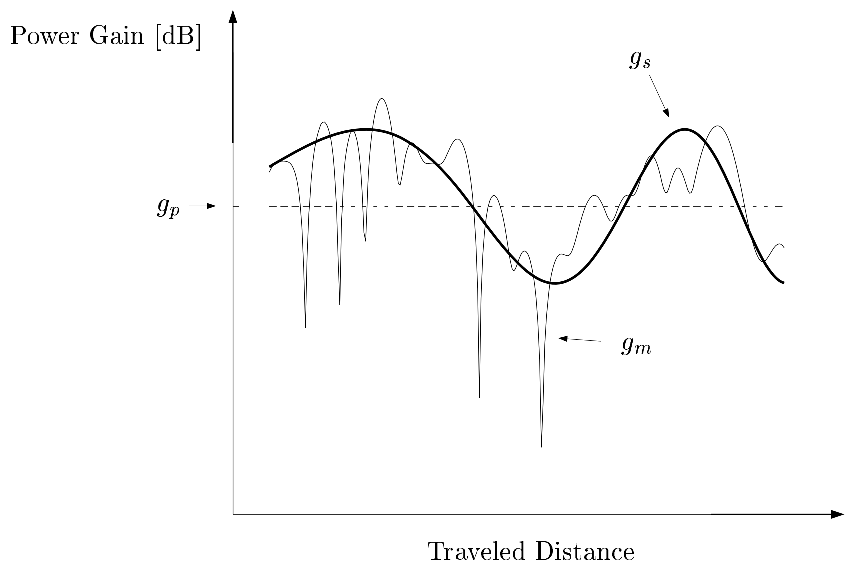

Figure 2.3: The model for radio wave propagation comprises path loss (g_p), shadow fading (g_s) and multipath fading (g_m).

of MS number 1. The receiver observes the desired signal and several interfering signals plus thermal noise.

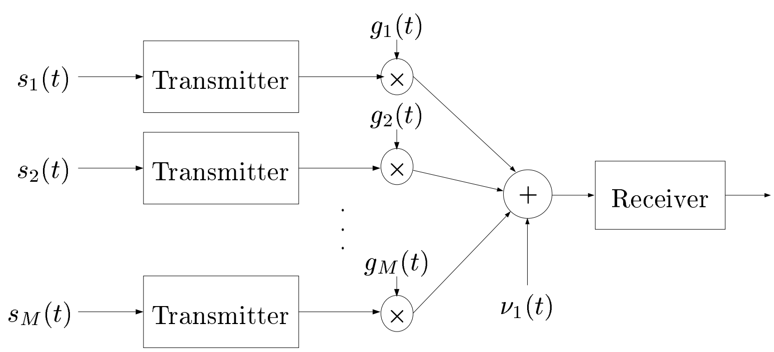

Figure 2.4: Simple model of a multi-user system. Note that the radio channels are characterized by their power gains g_i described in section 2.2. The signal $\nu_1(t)$ represents the thermal noise.

One important choice when designing a multi-user communication system is the choice of carrier signals, and we will divide them into two categories: orthogonal and non-orthogonal signals. The reason is that there are some characteristic differences, which will be pointed out in the following two sections.

2.3.1 Orthogonal Signals

When the signals are orthogonal, they can be seen as orthogonal base vectors spanning the signal space. Therefore the receiver only has to extract the energy along the s_1 dimension in the signal space in order to recover the information. We will not analyze the receiver structure in more detail, and instead focus on the commonly used orthogonal signals.

The first approach is to separate the users in the frequency domain. Suppose we have an available frequency band of W Hz, and that each user needs a bandwidth of w Hz. We can then divide W into $N_w = W/w$ sub-bands of w Hz each. This is referred to as *Frequency Division Multiple Access, FDMA* (Figure 2.5a), and it has been very popular throughout the years mainly because it is well suited for analog technology. The main challenge is the frequency synchronization, which is needed to extract the sub-band of interest. FDMA is the technique used in systems of first generation, such as NMT, AMPS, and TACS. The sub-band bandwidth used in these systems are 25-30 kHz.

Similarly, we can separate the users in the time domain using *Time Division Multiple Access, TDMA* (Figure 2.5b). Then each user is allowed to use the entire frequency band W Hz, but only at assigned time slots. Let each time slot have a duration of τ seconds, and if the users use the slots in a round robin fashion with a cycle length of T seconds, there are $N_\tau = T/\tau$ channels available in the system. TDMA has the advantage over FDMA that the receiver of the mobile station is only used $1/N_\tau$ of the time. During the rest of the time it can be used for scanning other channels. Since the message is sent discontinuously, TDMA is better suited for digital technology than for analog and the challenge is time synchronization.

Pure TDMA solutions are rare and instead hybrid FDMA/TDMA (Figure 2.5c) is used, where the spectrum is divided up in N_w frequency bands, which each are divided into N_τ time slots. One example is D-AMPS, where each 30 kHz sub-band in AMPS is divided into three time slots, resulting in a threefold capacity increase. In GSM, the sub-bands of 200 kHz are divided up into eight time slots. Compared to the 25 kHz channels in NMT there is no capacity increase at all. Instead this is used to enable more reliable communication.

In GSM there is an optional frequency-hopping pattern meaning that the mobile is using a different sub-band each time slot. This hopping sequence is determined by a code, and therefore this technique is referred to as *Frequency Hopping Code Division Multiple Access, FH-CDMA*. Altogether, the scheme can be seen as the hybrid FDMA/TDMA/CDMA (Figure 2.5d).

2.3.2 Non-Orthogonal Signals

To avoid the problems of frequency and time synchronization, we can use signals that are "almost orthogonal". Each user is assigned a code and is then transmitting using the entire frequency band. The receiver extracts the desired signal by correlating the received signal and the code. This spread-spectrum technique is referred to as *Direct Sequence Code Division Multiple Access, DS-CDMA*.

Consider the uplink, and assume that there are two mobile stations in the service area, where one is close to the base station and one is far away. If both mobile stations are transmitting using the same power level, the received

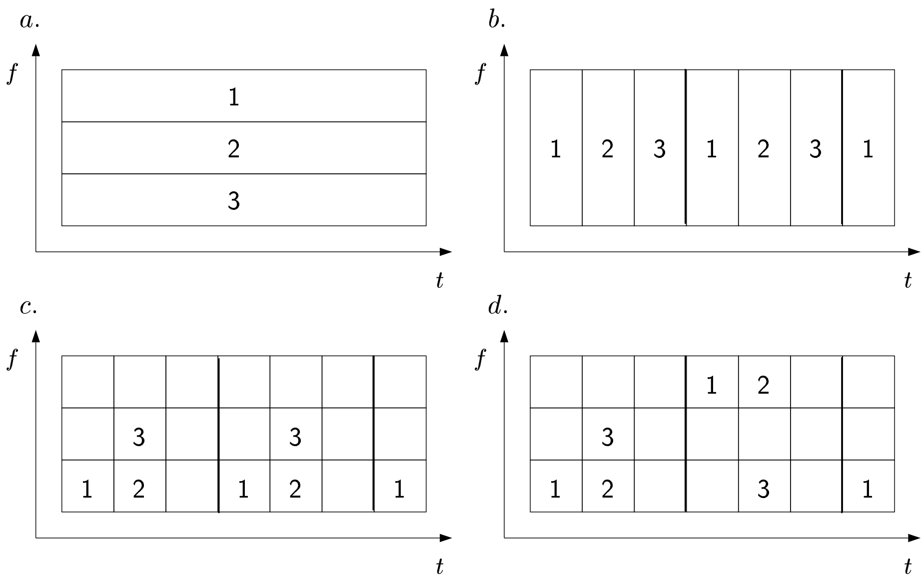

Figure 2.5: Different multiple access techniques using orthogonal signals. The users 1, 2, 3 may be separated either in frequency or in time or both. a. FDMA, b. TDMA, c. FDMA/TDMA, d. Frequency hopping FDMA/TDMA.

powers at the base station might differ by several orders of magnitude, due to different power gains of the signals (recall Section 2.2). The signal extraction at the receiver based on correlation works fine when the powers of received signals are roughly the same. This is not the case in the above situation, where the signal from the distant mobile station is drowned by the signal from the close one. Therefore we have to use appropriate power levels in order to tamper this *near-far effect* [14]. In the downlink, this is not a problem, since all the signals originate from the same transmitter.

This technique is used today in the narrowband system IS-95, where all terminals communicate on a frequency band of 1.25 MHz. In the systems of third generation the same technique will be used, with the major difference that the frequency bands will be wider. That will enable higher data rates and mitigate fading better.

2.4 Cellular Radio Systems

When the service area is large, one base station will not suffice. Instead the service area is divided into a large number of cells, which has given rise to the name *cellular radio systems*. Each cell is served by a base station (BS) and within the cell the situation is similar to what is described in Section 2.3.

The size of different cells varies very much between rural and urban areas and this is due to the limited number of users one cell can serve. In rural areas few and large cells are sufficient to meet the needs, and the radius may be several tenths of kilometers. In denser populated areas where cellular phones are common, there is a need for smaller and more numerous cells, serving an area of radius down to about 100 meters. To meet the needs in the central parts of cities, it is getting more common to use cells consisting of a short part of a street (*micro cells*) or a room or a floor of a building (*pico cells*).

Usually the cells are depicted as hexagonal, but in reality their size and form are irregular and depending on the terrain and the propagation conditions. Designing a cellular system involves extensive *cell planning*. Among other things this involves determining clever cell sites to get appealing propagation conditions and cell sizes to meet the needs for communication at the present and in a near future. In order to use the hardware efficiently it is more and more common to co-locate three base station antennas and use *sectorized* antennas covering a sector of 120° each. When the antenna is radiating in all directions the term *omnidirectional* antenna is used.

The operator of the cellular system is assigned a frequency band to use in the service area. This spectrum is split up in a number of channels (waveforms) based on the multiple access scheme chosen for the operation of the system. When assigning these channels to the base stations, the path loss is actually favorable. Within the cell, the transmitted signal from the BS can be received by the MS at a reasonable signal strength, but at some distant point outside the cell, the power of the signal is neglectable compared to the noise. Therefore the channels can be *reused* in the service area. The available channels are divided into K channel groups and each group are assigned to some base stations as exemplified in Figure 2.6. If we assume a hexagonal cell pattern, the possible *reuses* K are given by $K = a^2 + ab + b^2$, where a and b are natural numbers. This yields $K = 1, 3, 4, 7, 9, 12, 13, \ldots$. Note that $K = 1$ corresponds to the trivial case where all channels are used in every cell.

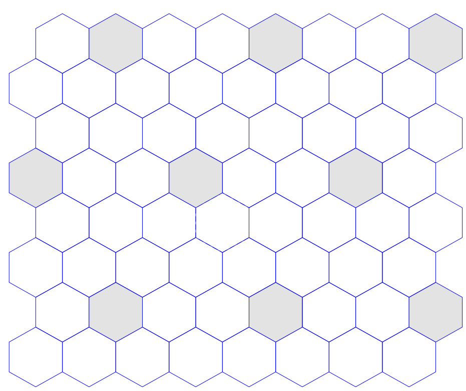

Figure 2.6: The same channel group is reused in different cells in the network. This example shows the cells, to which one channel group is assigned, when we are applying a reuse $K = 9$.

In order to keep the presentation clear we will consider the case of orthogonal signals. Furthermore, let us focus on a specific downlink channel and on the mobile stations and base stations using that channel. The terminals are numbered, so that mobile station i is connected to base station i. (Since we focus on one single channel, only one MS is connected to each BS on this channel.) Furthermore, the power gain from base station j to mobile station i is denoted $\bar{g}_{ij}$. The information about all downlink power gains on the channel at a time instant t can be condensed into the $G - matrix$ of the channel, $\bar{\boldsymbol{G}}_c(t)$. Assume that there are m connections established on the channel. Then this G-matrix is given by

$$\bar{\boldsymbol{G}}_c(t) = \begin{pmatrix} \bar{g}_{11}(t) & \cdots & \bar{g}_{1m}(t) \\ \vdots & \ddots & \vdots \\ \bar{g}_{m1}(t) & \cdots & \bar{g}_{mm}(t) \end{pmatrix}. \tag{2.3}$$

Thus the first column contains the gains from base station 1 to the different mobile stations. This matrix is time variant, since each of the power gains is time variant and since the dimension of the matrix varies with time when mobiles place new calls or hang up. There are actually two G-matrices: one for the uplink and one for the downlink. This is due to the use of different frequency bands, as well as different propagation conditions and antennas for the base stations and the mobile stations.

Assume that base station i is transmitting using the power $\bar{p}_i(t)$. The corresponding connected mobile station will experience a desired carrier signal power $\bar{g}_{ii}(t)\bar{p}_i(t)$, thermal noise $\bar{\nu}_i(t)$ and an interference, which is the sum of the powers from all other base stations. See Figure 2.7 for a situation of three interferers. Since this interference is emanating from users on the same channel, it is referred to as *co-channel interference.* When we are employing a large frequency reuse or there are few users in the system, the interference is neglectable compared to the noise, and the system is *noise-limited.* In the opposite situation when we employ a small reuse and several mobile stations are active, the system is *interference-limited* due to the dominating interference.

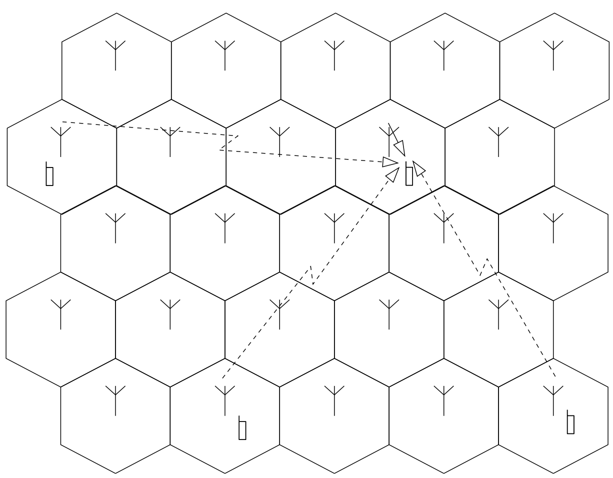

Figure 2.7: Co-channel interference in a network employing frequency reuse. The received signal at the mobile station consists of the desired signal (solid), interfering signals from other base stations (dashed) and thermal noise. The reuse pattern is the same as in Figure 2.6 where the reuse $K = 9$.

Moreover, we can define the *carrier-to-interference* ratio (C/I) at mobile station i as

$$\bar{\gamma}_i(t) = \frac{\bar{C}_i(t)}{\bar{I}_i(t) + \bar{\nu}_i(t)} = \frac{\bar{g}_{ii}(t)\bar{p}_i(t)}{\sum_{j \neq i} \bar{g}_{ij}(t)\bar{p}_j(t) + \bar{\nu}_i(t)}. \tag{2.4}$$

Sometimes the term *Signal-to-Interference Ratio* (SIR) is used instead. This quantity is commonly used when analyzing the perceived transmission quality at the receivers.

In a DS-CDMA system, all the users are using the same frequency channel. Hence the frequency planning process of assigning channels to the base stations is avoided. It can be seen as employing a reuse of $K = 1$. Therefore everybody is interfering with each other in the network and contributes to the interference at each receiver.

When implementing a simulation model, only a finite cells are considered in a bounded service area. In the central parts of the service area, the situation is realistically modeled, but near the boundaries, the interference is considerably less due to less interferers. One possible solution would be to implement a large service area, but only consider a central area, where the boundary effects can be neglected. A more efficient approach is to consider the left and right ends, and the top and bottom ends to be connected in a torus fashion. This approach is commonly referred to as *wrap around*. Thereby a mobile station in the lower left corner of the service area is actually very close to, and consequently interfered by, a base station in the upper right corner.

2.5 Radio Resource Management

In this chapter we briefly discuss *Resource Allocation Algorithms* (RAA). For a more extensive overview of RAA we refer to Zander [15].

Consider a mobile communication system covering a certain service area as described in Section 2.4. In this network the M active mobile stations (MS) are served by B base stations (BS), numbered from the sets

$$\begin{aligned} \mathcal{M} &= \{1, 2, \dots, M\}. \\ \mathcal{B} &= \{1, 2, \dots, B\}. \end{aligned}$$

The frequency spectrum assigned to the network operator for radio links is divided into C channel pairs (waveforms), numbered from the set

$$\mathcal{C} = \{1, 2, \dots, C\}.$$

The process of dividing up the spectrum into channels is based on the multiple access method chosen, see Section 2.3. We need a pair of channels for each communication link, since it consists of an uplink and a downlink. When a mobile station is admitted to the network a radio link has to be established. The following has to be assigned to the MS:

- A base station from the set $\mathcal{B}$.
- A channel pair from the set $\mathcal{C}$.
- Transmitter powers for the BS and the MS.

The objective of a *resource allocation algorithm* (RAA) is to update these assignments during the call in order to maintain an acceptable quality while serving as many users as possible.

In MOSE, the focus is on the effects of controlling the transmitter powers, and therefore it is assumed that the other choices are updated separately. It may be beneficial to update all three concurrently, but this is not considered in MOSE. For simulation reasons, however, a simple base station assignment algorithm is used, which is further described in Section 2.6.

Furthermore, as shown in Appendix A, we can without loss of generality, assume that the system is based on orthogonal signals and focus only on the communication on a specific channel. Therefore, MOSE is based on one single channel, available in every cell.

2.6 Mobility

The main reason for slowly time varying channels is the fact that the mobile stations are moving. This result in shadow fading channels as described in Section 2.2.2. Several models for mobility can be applied, and at the moment, the following four mobility behaviors are implemented:

- **Fixed location** throughout the simulation.
- **Constant velocity** in a random but constant direction.
- The two previous are combined using a **finite state machine**, where the two states are given by the previous models. The transition probabilities are p_{start} and p_{stop} respectively, and each time a mobile starts moving, it moves in a constant, but random direction.
- In **Manhattan random walk** the mobile is moving at constant velocity, but at each sample instant it may turn left or right or move straight ahead, with each case equally probable.

In order to be fairly realistic, different mobile stations may use different mobility behaviors in MOSE.

When moving in the service area, there is a risk of entering a different cell, and it may be more desirable to connect to a different base station. Therefore, *handover* or *handoff* algorithms are needed. Since only one channel is simulated in MOSE, the handover situation is somewhat delicate. In the case when the interesting base station is vacant, handover is possible, but otherwise not. A simple solution (applicable only in a simulator) is to allow handover when possible, and to force the mobile to turn in the opposite direction, when not. Another solution is to never allow handover, and always turn the mobiles in the opposite direction when reaching the cell boundary. Both approaches are implemented in MOSE.

2.7 Summary

Basic models in mobile communications systems have been reviewed, and related to the models actually implemented in MOSE. In summary, we stress the restrictions of the implementation, and the reasons behind.

The power gain from transmitter to receiver can be separated in three components. Firstly, the long time average, the *path loss* is depending mainly on the distance to the receiver. Secondly, the power is shadowed by obstacles in the terrain resulting in *shadow fading*, which is correlated spatially. Finally, the gain is subject to rapid fluctuations due to *multipath* propagation. Since the sample interval in MOSE is considerably larger than these fluctuations, these are averaged out in the measurements, and therefore not modeled in MOSE.

The service area of a cellular radio system is covered by a cell layout, modeled as hexagonal cells. Near the boundaries, the interference is less due to fewer interferers. These boundary effects are avoided by "wrapping" the service area in a torus fashion.

Radio resource management is essentially about choosing the appropriate base station, channel pair, and transmitter powers, and to update the choice on a regular basis. In MOSE, the focus is mainly on power control algorithms, even though some simple base station assignment algorithms are considered for simulator technicalities. It is shown that without loss of generality, we can therefore assume that the system is based on orthogonal signals, and focus only on the communication on a specific channel. This motivates why MOSE is based on one single channel, available in every cell.

In order to investigate the tracking abilities of algorithms, mobility of mobile stations has to be modeled. At the moment four different mobility behaviors are implemented, and different mobile stations may use different behaviors in a simulation.

Chapter 3

Power Control

3.1 Aspects of Power Control

Let us assume that the appropriate base stations are assigned and channels allocated. Then the remaining problem is to update the output powers of the transmitters. When characterizing the necessary power control algorithms, we find the following aspects interesting:

- **Centralized/Decentralized Controller.** A centralized controller has all information about the established connections and power gains at hand, and controls all the power levels in the network. A decentralized controller is only controlling the power of one single transmitter, and the algorithm is only relying on local information. The latter case is the only practical one, since a centralized controller requires extensive control signaling in the network, and will suffer from additional time delays.

  Note that the distinction is primarily between the type of information used when computing the output powers. Even if an algorithm is considered to be decentralized, it is not necessarily physically located in the mobile station. Instead, the power levels may be computed in the base stations, and distributed to the corresponding transmitters. This master-slave relationship facilitates software updates and support.

- **Quality Measure.** Speech quality is a very subjective quantity. People have argued that SIR is an adequate objective measure, and it has been used extensively in previous works, even though it is far from ideal. However, it gives a rough estimate of the quality and is straightforward to employ.

- **Available Measurements.** Even if we find the optimal quality measure, this will most likely not be possible to measure. Usually the measurements are given in reports comprising a *Quality Indicator* (QI), reflecting the quality and a *Received Signal Strength Indicator* (RSSI), reflecting the received signal strength at the receiver. These values are coarsely quantized in order to use few bits. Thus an important question is to determine which quantities that can and should be estimated given the available measurements.

- **Constraints.** The output power levels are limited to a given set of values due to hardware constraints. This includes quantizing and the fact that the output power has an upper and a lower limit. Additionally, the various standards include different constraints. For instance in GSM, there are channels in the network requiring the use of maximum power, and in D-AMPS all three time slots on the same carrier have to use the same power level.

- **Time Delays.** Measuring and control signaling takes time, which results in time delays in the network. These are primarily of two kinds. Firstly it takes some time to measure and report the measurements to the algorithm, and secondly we have a time delay due to the time it takes before the computed power is actually used in the transmitter.

Hence we can describe the surrounding environment, as seen by the power controller, as in figure 3.1. Note that the chosen quality measure is not necessarily measurable directly. Time delays are expressed using the delay operator q, defined by

$$q^{-n}p(t) = p(t-n).$$

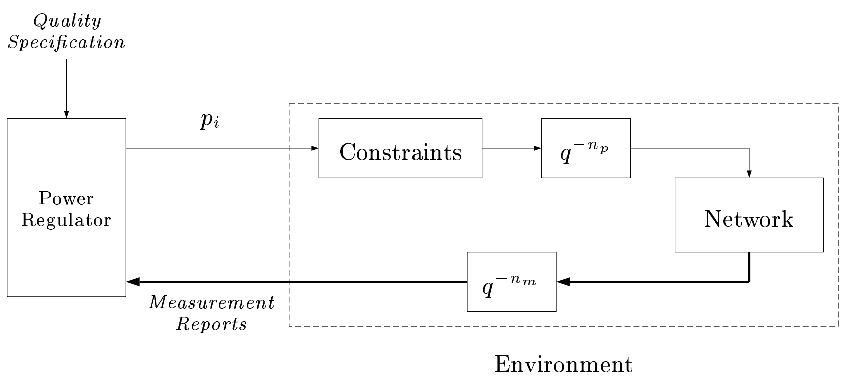

Figure 3.1: The surrounding *Environment* as seen by a decentralized controller, when considering time delays and constraints. The *Network* block incorporates the effects caused by the radio channel, such as power gain, noise and interfering transmitters.

When the algorithmic properties of the power controller, e.g. convergence and settling time, are to be studied, it may be easier to assume that the interesting values are at hand, and that quality is related to simple measures. Then we refer to this power controlling component as the *Power Control Algorithm* (PCA). This includes most of the algorithms developed in this area to date. For example, it is common to assume that the transmission quality is only dependent on the SIR and that this value is at hand. On the other hand when discussing a complete solution that fits into interfaces of real systems, we use the term *Power Regulator* (PR). For further details, we refer to [1].

In MOSE, the focus is on the behavior and dynamics of power control algorithms. Issues related to quality, are assumed to be dealt with in outer loops, which aim to update the reference values to the inner loops. Consequently, SIR is a relevant quality measure, and the objective can be expressed as

$$\gamma_i(t) \geq \gamma_{tgt_i}(t), \ \forall i,$$

where $\gamma_{tgt_i(t)}$ are the reference values set by outer loops. In MOSE, these values are constant during the simulations.

3.1.1 Time Delays

Measuring and signaling in cellular systems take time, which result in delayed signals. As pointed out in Section 3.1, there are two main reasons for time delays. Firstly it takes some time before a computed power level actually will be used and thereby observed by others. Additional delays are caused by the fact that power update commands are only allowed to be transmitted at certain time instants. Together they result in a total delay of n_p samples. Secondly, the measuring procedure takes time, and again these measurements are only reported to the power control algorithm at certain time instants, resulting in a delay of n_m samples. In total there is a delay of $n = n_p + n_m$ samples in the local loops.

Time delays are expressed using the delay operator q defined by

$$q^{-n}p(t) = p(t-n)$$

3.1.2 Nonlinearities

Due to physical limitations in the hardware, the output power levels are bounded from above by p_{max} and from below by p_{min}. In addition, the power levels are quantized, and normally, a uniform quantization in dB-scale is used. Usually, these nonlinearities are referred to as *constraints* in the literature.

There are also nonlinearities introduced by the software. In some standards, there are channels requiring the use of maximal powers, and when using different channels during a call, this is definitely a nonlinearity. It is also possible to incorporate a nonlinearity in the power control algorithm. For instance, in some schemes, the power level is changed only by a fixed step. Thus the rate of change is limited, and such a component is referred to as a *rate limiter*.

3.1.3 Measurement Filters

The measurements or estimates may be corrupted by noise and therefore a smoothing filter $F(q)$ can be applied, in order to even out rapid fluctuations due to noise. In essence, the smoothing filter describes the effects and errors due to estimation in the receiver. The smoothing filter $F(q)$ is completely arbitrary, but common choices, which both are implemented in MOSE, are described below

- **Local Average**. The output of the filter is the mean value of the last L input values, and thus $F_{LA}(q)$ is given by

$$F_{LA}(q)\hat{\gamma}_i(t) = \frac{\hat{\gamma}_i(t) + \ldots + \hat{\gamma}_i(t-L+1)}{L} = \frac{1 + \ldots + q^{-L+1}}{L}\hat{\gamma}_i(t). \quad (3.1)$$

  The parameter L is commonly referred to as the *window length*.

- **Exponential Forgetting**. In the previous approach, the values are weighted together using an equal weight. A batch containing the last L values is also needed. Another approach is to weight the input values $u(t)$ differently, using larger weights on the more recent values. This can be achieved by the following recursion, where the inputs are given by $u(t)$ and the filter output by $y(t)$.

$$y(t+1) = \lambda y(t) + (1-\lambda)u(t+1) \ , \quad 0 \leq \lambda < 1$$

Using the delay operator, the smoothing filter $F_{EF}(q)$ can be defined by

$$y(t) = F_{EF}(q)u(t) = \frac{(1-\lambda)q}{q-\lambda}u(t). \tag{3.2}$$

The number of values that essentially contribute to the filter output is depending on the *forgetting factor* λ. As a rule of thumb, it is argued that the number of contributing terms, L_{EF}, can be approximated by

$$L_{EF} \approx \frac{1}{1-\lambda} \tag{3.3}$$

3.2 Centralized Algorithms

As discussed in Section 3.1, the drawback with centralized power control algorithms is that they require severe signaling. Thus, the main interest in these algorithms, at least for cellular systems, has not been motivated by their practical use, but rather by their ability to give bounds on the performance of the distributed algorithms.

The development of centralized algorithms started with the article [16] by Aein from 1973, dealing with satellite communication systems. Here the term *C/I balancing* was introduced for a strategy of power control aiming for all users to have the same C/I, and a solution based on an eigenvalue problem was proposed.

Nettleton and Alavi extended these results [17, 18, 19] and applied them to spread spectrum cellular radio systems. This section will be close to the spirit of [20] by Zander, where these centralized algorithms were given an interpretation as an "optimal" solution, in a sense that we will come back to. This approach was further refined by Grandhi, Vijayan, Goodman and Zander [21]. This section will review the results in the aforementioned articles, which are all rather similar.

In the following analysis only values at the same time instant t are considered, and therefore this time index will be suppressed for clarity. Assume that we would like to make a power assignment $\bar{p}_i$ such that each user experiences a C/I ratio of at least $\bar{\gamma}_0$ (compare to Equation (3.1)). This can be rewritten as

$$\bar{\gamma}_i = \frac{\bar{g}_{ii}\bar{p}_i}{\sum_{j\neq i}\bar{g}_{ij}\bar{p}_j + \bar{\nu}_i} = \frac{\bar{p}_i}{\sum_j \bar{Z}_{ij}\bar{p}_j - \bar{p}_i + \bar{\eta}_i} \geq \bar{\gamma}_0 \ , \quad \forall i, \tag{3.4}$$

where $\bar{Z}_{ij}$ and $\bar{\eta}_i$ are defined by

$$\bar{Z}_{ij} = \frac{\bar{g}_{ij}}{\bar{g}_{ii}}, \ \bar{\eta}_i = \frac{\bar{\nu}_i}{\bar{g}_{ii}}.$$

Furthermore introduce the matrix $\bar{\boldsymbol{Z}}$ with components $\bar{Z}_{ij}$. At this point we can note that $\bar{\boldsymbol{Z}}$ is a nonnegative matrix, which means that all its components are nonnegative. It is also worth to notice that $\bar{\boldsymbol{Z}}$ has a unit diagonal, and if the links have been established between the transmitters and receivers having the best power gain, the off-diagonal elements will be smaller than one.

Let $\bar{\boldsymbol{p}}$ denote a vector containing the $\bar{p}_i$'s and $\bar{\boldsymbol{\eta}}$ a vector with the $\bar{\eta}_i$'s. Then equation (3.4) can be rewritten as

$$\frac{1+\bar{\gamma}_0}{\bar{\gamma}_0}\bar{\boldsymbol{p}} \geq \bar{\boldsymbol{Z}}\bar{\boldsymbol{p}} + \bar{\boldsymbol{\eta}}. \tag{3.5}$$

The inequality in (3.5) is solved using linear programming (LP). However, when neglecting the thermal noise, the optimal solution is given by the solution to an eigenvalue problem.

3.3 Decentralized Algorithms

In real implementations, distributed algorithms are the only practical options. Several algorithms have been proposed, and here we review some of the, in our opinion, most interesting algorithms.

3.3.1 Distributed Balancing Algorithm

As noted in the previous section, a centralized algorithm may break down to solving an eigenvalue problem. Based on results for iterative computations of eigenvectors, Zander proposed the *Distributed Balancing* (DB) algorithm

$$\bar{p}_i(t+1) = \beta\bar{p}_i(t)\left(1 + \frac{1}{\bar{\gamma}_i(t)}\right). \tag{3.6}$$

At first sight the DB algorithm appears to be distributed, since it is based only on $\bar{\gamma}_i(t)$, which is a measurements of the local C/I. However, it turns out that the choice of β is problematic, since it may make $\bar{\boldsymbol{p}}$ drift towards zero or infinity, if not appropriately chosen. This choice of β can be seen as a normalization procedure, and it must be based on global information. Thus this is not a fully decentralized algorithm.

3.3.2 Distributed Power Control Algorithm

The Distributed Power Control (DPC) algorithm, which is a slight modification of the DB algorithm, was suggested by Grandhi, Vijayan and Goodman [22]

$$\bar{p}_i(t+1) = \beta\frac{\bar{p}_i(t)}{\bar{\gamma}_i(t)}. \tag{3.7}$$

I has been proved [23, 1] that the DPC algorithm converges faster than the DB algorithm, an is therefore a more appealing choice of algorithm.

3.3.3 I-controller

The previous two algorithms work fine in ideal cases, but when considering more realistic cases, more careful control action is needed. This is achieved by adding the parameter β and use the following algorithm

$$\bar{p}_i(t+1) = \bar{p}_i(t) \left(\frac{\bar{\gamma}_{tgt_i}(t)}{\bar{\gamma}_i(t)} \right)^{\beta}. \tag{3.8}$$

Its convergence was proven in [1], and it is referred to as an *I-controller*. This is evident when applying logarithms on each side of (3.8), revealing the integrating action of the algorithm.

$$p_i(t+1) = p_i(t) + \beta(\gamma_{tgt_i}(t) - \gamma_i(t)). \tag{3.9}$$

3.3.4 PID Control

In cases when we want a signal to track a certain target value, and it is hard to model the system completely, a PID-controller [24] might be a good choice. It consists of a proportional (P), an integrating (I) and a differentiating (D) part. In general it is described by the Equations (3.10a-c), where we have denoted SIR by γ and target SIR by γ_{tgt} for simplicity. We also introduce the sampling interval T_s (typically 0.48s in GSM), the integrator state $x(t)$, the error $e(t)$ between the target SIR and the measured SIR, and finally the PID parameters K_p, K_i, K_d.

$$e(t) = \gamma_{tgt}(t) - \gamma(t) \tag{3.10a}$$

$$x(t+1) = x(t) + K_i T_s e(t) \tag{3.10b}$$

$$p(t+1) = K_p e(t) + x(t+1) + K_d \frac{e(t) - e(t-1)}{T_s}. \tag{3.10c}$$

When the measurements are noisy, the differentiating part might over-react, and the solution is either to omit the D component or to apply an approximate differentiation. The latter is achieved by the use of a low pass filter.

In order to counteract the effects of the constraints, we first have to identify them. If the computed output power is p, we let $f(p)$ denote the true output of the transmitter. Thus $f(\cdot)$ describe the total effect of hardware and external constraints. These effects can be reduced or eliminated by applying *anti-reset windup* [24]. One common approach is to update the integrator state after computing the power level in (3.10c), which is described in (3.11).

$$x(t+1) = x(t+1) + \frac{T_s}{T_t} \left(f\left(p(t+1) \right) - p(t+1) \right) \tag{3.11}$$

If $T_t = T_s$ the integrator state will correspond to the actual output, which is generally desirable. However, when using derivative action (corresponds to $K_d > 0$) spurious errors may accidently reset the integrator, and it has been suggested [24] to use $T_t = \sqrt{K_d/K_i}$ as a rule of thumb.

3.3.5 AAW-algorithm

The problem with the distributed algorithms listed above is to assign the appropriate $\bar{\gamma}_{tgt}$, the target C/I that the algorithms will strive towards. If the value is set too high, it is not possible to support all the mobiles, and they might experience the "party-effect" in the network. It occurs when one user increases its power and thereby the interference at other receivers. These users may react by increasing their powers which will increase the interference at the first user, who will find it necessary to increase its power and so on. If the power is bounded from above by a maximum level, determined by the physical limits of the system, some mobiles may increase their powers to this maximum, without achieving the specified target.

An attempt to counteract this effect and to employ graceful degradation in the systems is proposed by Almgren, Andersson and Wallstedt in [25]. The main idea is that a user requiring a high transmission power has to accept a lower quality, and the algorithm is given by

$$p_i(t+1) = \alpha - \beta(\gamma_i(t) - p_i(t)). \tag{3.12}$$

A convergence proof of the algorithm in (3.12) is disclosed in [26]. The result also holds when considering bounded output powers.

This algorithm can be rewritten as

$$p(t+1) = \beta p(t) + \beta(\gamma_{tgt} - \gamma(t)).$$

In addition, anti-reset windup can be applied and if we introduce a time varying $\gamma_{tgt}(t)$ we obtain

$$e(t) = \gamma_{tgt}(t) - \gamma(t) \tag{3.13a}$$
$$x(t+1) = \beta I(t) + \beta e(t) \tag{3.13b}$$
$$p(t+1) = x(t+1) \tag{3.13c}$$
$$x(t+1) = x(t+1) + \frac{T_s}{T_t}\left(f\left(p(t+1)\right) - p(t+1)\right). \tag{3.13d}$$

This algorithm will be referred to as the *AAW algorithm.*

Chapter 4

Examples

The ambition with MOSE has been to create a user-friendly and intuitive graphical user interface. Hopefully, the impatient finds the environment easy to explore on his own. However, a few examples may speed up the process and give a rough idea of the basic use.

Start MOSE from the command line

`>> MOSE`

4.1 A Simple Example

This simple example serves as a walk-through and covers basic simulations.

- First, we have to define the cell layout of the service area. Choose `Network Configuration...` from the `Setup` menu. The default settings will be sufficient, so click `OK`.
- Next, the mobility behaviors have to be defined. Choose `MS Behavior...` from the same menu and confirm the default settings by clicking `OK`.
- In order to define mobile stations in the network, choose `MS Editor...` from the `Setup` menu. Add mobiles by clicking once on `Add Mobile`, drag to the desired location, and click again to release the mobile. Repeat the process to add two more mobiles. Remember that MOSE is using only one channel, so assign one mobile per cell for proper assignments. The configuration may look like in Figure 4.1
- Clink on `Set Behaviour` to enable behavior selection. Now, click on each mobile and the corresponding behavior toggles between the defined possibilities. The behaviors are color coded and the interpretation is given in the status bar below the network. Assign behavior 4 to all three mobiles, and confirm the settings by clicking `OK`.
- Define the simulation via `Parameters...` in the `Simulation` menu. Select `Shadow Fading` and choose `DPC` as the power control algorithm. Confirm by clicking `OK`.

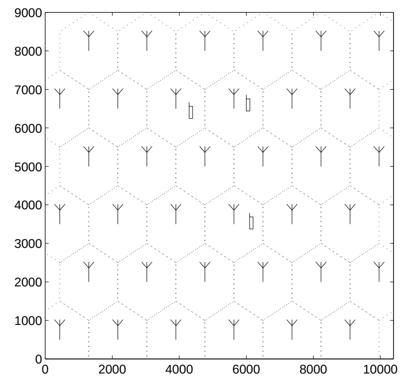

Figure 4.1: A network of 6 × 6 cells and three mobiles.

- Bring up the control panel for simulations via `Simulation Control...` in the `Simulation` menu. Click `Run` to start the simulation. When simulation is finished, the `Simulation Results` window pops up. Use the popup-menus to examine the simulation result. A C/I above 10 dB may be considered as satisfactory. Your result may look like in Figure 4.2

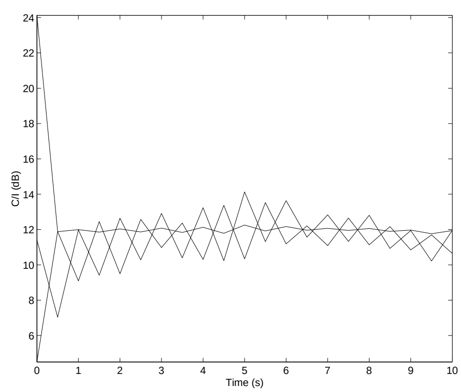

Figure 4.2: C/I as a function of time when simulating the network in Figure 4.1. Note that the result is depending on the realization of the shadow fading.

4.2 Quick Start

At some point, most work is concentrated to investigating algorithms, and to step through all setup windows becomes very tedious. Therefore, a *Quick Start* facility is implemented. Choose `Quick Start` from the `File` menu. Then the following settings will be employed automatically:

1. The default network configuration.
2. The default mobility behaviors.

3. Five mobile stations assigned fixed locations (behavior 1), distributed as in Figure 4.3.

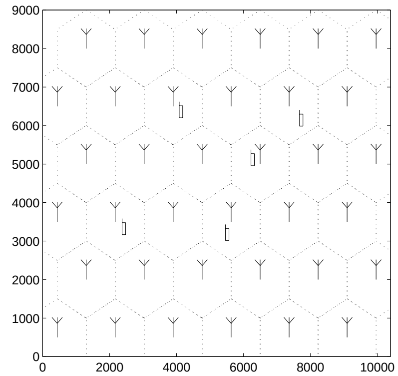

Figure 4.3: Distribution of mobiles assigned using *quick start*.

4. Measurement delay and power output delay of one sample each (in essence a time delay of one sample, since one power output delay is unavoidable in practice). Otherwise the default system parameters.

5. The default controller parameters.

6. The default measurement filter.

7. Saturation and quantization limiting the output power.

It also brings up the simulation control panel and the simulation parameters window. Convenience may be the first reason to use quick start, but it is also relevant to have a default setting defined, when comparing algorithms.

4.3 Step Response Evaluation

Applying a step change in the input signal to a controlled system is a common means to evaluate the performance of the controller. In a similar manner there is a *step response evaluation* implemented in MOSE. Consider a situation of four mobile stations transmitting using powers corresponding to acceptable quality. At $t = 0$ a fifth mobile is admitted into the network, see Figure 4.4. The actions of the control algorithm in use reveals its ability to handle abrupt changes in the network.

Choose `Test Cases Setup ...` from the `Test Cases` menu. Select `Step Response` from the `Test Objective` popup menu. The settings in `Environment Parameters ...`, `Controller Parameters ...` and `Output Power Limitations ...` in the `Setup` menu still apply. When the parameters are set satisfactory, press `Run`.

As an example, we study the DPC algorithm and note that it is not able to handle situation when subject to the delays set using quick start (in essence only a single sample), see Figure 4.5.

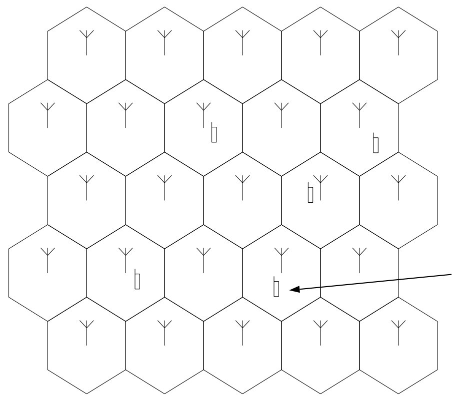

Figure 4.4: Part of the network in the simulation environment, where the active mobile stations are located. The arrow indicates the mobile station, which establishes a call at time instant $t = 0$.

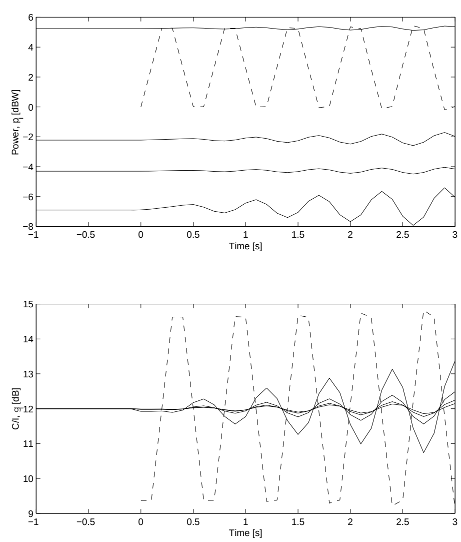

Figure 4.5: The action of the DPC algorithm when subject to the step response situation and a single time delay. The dashed line corresponds to the recently admitted mobile station, and the solid lines to the original four mobiles.

Appendix A

Means to Control the Resources

In order to define the controllable resources more formally and to see how they affect the transmission quality we need to start from a simple but relevant quality measure. The carrier-to-interference ratio C/I is commonly used as such a quality measure. Based on its definition, we will try to find a general framework which can be used both for orthogonal and nonorthogonal signals.

Consider the case of orthogonal signals. We focus on a specific downlink channel and on the mobile stations and base stations using that channel. The terminals are numbered, so that mobile station i is connected to base station i. Recall from Section 2.4 that the power gain from base station j to mobile station i is denoted by $\bar{g}_{ij}$, and that the power used by terminal i is denoted by $\bar{p}_i$. Hence, the C/I at mobile station i is given by

$$\bar{\gamma}_i(t) = \frac{\bar{C}_i(t)}{\bar{I}_i(t) + \bar{\nu}_i(t)} = \frac{\bar{g}_{ii}(t)\bar{p}_i(t)}{\sum_{j \neq i} \bar{g}_{ij}(t)\bar{p}_j(t) + \bar{\nu}_i(t)}. \tag{A.1}$$

It has been argued that the quality is acceptable when this ratio is above a certain threshold, i.e.

$$\bar{\gamma}_i(t) \geq \bar{\gamma}_0 \,, \ \forall i.$$

When extending the definition in (A.1) to include all the channels in the system and to cover both orthogonal and non-orthogonal signals, we obtain an intuitive definition of the control signals. These relate to the assignments of base stations, channel pairs and transmission powers, which were listed in Section 2.5.

In addition, we will disclose that with some obvious redefinitions, the C/I expression in (A.1) holds for both orthogonal and nonorthogonal signals. Without loss of generality we can therefore focus on the situation on a specific channel in the orthogonal case, when analyzing several aspects of these systems.

Systems Based on Orthogonal Signals

Consider the entire network, and assume that there are B base stations covering the service area, serving the M active mobile stations. Denote the power gain from base station j to mobile station i at time instant t by $\bar{g}_{ij}(t)$. We gather this information in the G-matrix of the network, $\bar{\boldsymbol{G}}(t)$, defined by

$$\bar{\boldsymbol{G}}(t) = \begin{pmatrix} \bar{g}_{11}(t) & \cdots & \bar{g}_{1B}(t) \\ \vdots & \ddots & \vdots \\ \bar{g}_{M1}(t) & \cdots & \bar{g}_{MB}(t) \end{pmatrix} \tag{A.2}$$

Note that unlike the G-matrix of a single channel (see Section 2.4), this matrix is most likely not square, since several mobile stations are connected to each base station. Let mobile station i be connected to base station b_i. There is a possibility that no mobile stations are connected to a certain base station. Thus it is appropriate to let the number of the mobile station identify an established connection because of the one-to-one correspondence. Furthermore, define θ_{ij} as

$$\theta_{ij} = \begin{cases} 1 & \text{if base station } j \text{ is interfering on the} \\ & \text{channel used by mobile station } i \\ 0 & \text{otherwise} \end{cases}$$

This means that $\theta_{ib_i} = 0$, since the base station b_i is connected to, not interfering with, the mobile station i. Hence we get the following alternate expression for the C/I at mobile station i

$$\bar{\gamma}_i(t) = \frac{\bar{g}_{ib_i}(t)\, \bar{p}_{b_i}(t)}{\sum_{k=1}^{M} \bar{g}_{ib_k}(t)\, \bar{p}_{b_k}(t)\, \theta_{ib_k} + \bar{\nu}_i(t)}. \tag{A.3}$$

Hence an established connection, identified by the connected mobile k, contributes to the interference at mobile station i with a signal sent from base station b_k, if θ_{ib_k} is nonzero. The interference at mobile station i can thus be written as a sum over the M active mobiles.

As mentioned earlier, the uplink is more or less analogous. One difference is that we have to discuss the C/I at the base station with respect to a connected mobile station i. Thus the C/I at base station b_i is given by

$$\bar{\gamma}_{b_i}(t) = \frac{\bar{g}_{ib_i}(t)\, \bar{p}_i(t)}{\sum_{k=1}^{M} \bar{g}_{kb_i}(t)\, \bar{p}_k(t)\, \theta_{kb_i} + \bar{\nu}_{b_i}(t)}. \tag{A.4}$$

Note that we have used $\bar{g}_{ib_k}$ to denote the power gain between mobile station i and base station b_k both in the uplink and the downlink. In general these are different, and thus the network is not reciprocal.

Adjacent Channel Interference

Even if the signals are orthogonal when transmitted, the radio channel may affect this orthogonality. Time delays and lack of synchronization in the entire network, as well as fading and other effects violate the orthogonality. Hence there is an imminent risk of experiencing interference from adjacent channels at the receiver as well.

The G-matrix of the network is still defined as in (A.2). However, the matrix θ_{ij} is defined slightly different. In the previous section, the element corresponding to base station j and mobile station i was equal to zeros when using different channels. In this case it will be defined as a small value less than one describing this leakage between channels. Therefore the C/I expressions in Equations (A.3) and (A.4) still holds.

Systems Based on Non-Orthogonal Signals

The G-matrix of the network can be defined as in (A.2). Furthermore, if we define θ_{ib_k} by

$$\theta_{ib_k} = \begin{cases} \text{cross-correlation between the codes} & \\ \text{used by mobile stations } i \text{ and } k & , i \neq k \\ 0 & , i = k \end{cases},$$

the alternate expressions for the carrier-to-interference ratio in (A.3) and (A.4) still hold. If perfect correlation is represented by unity, θ_{ib_k} takes values between zero and one. As a simple model, we can assume that

$$\theta_{ib_k} = \begin{cases} 1/N_c & , i \neq k \\ 0 & , i = k \end{cases}$$

where N_c is related to the length of the code. This yields the following expression for the C/I at base station b_i

$$\bar{\gamma}_{b_i}(t) = \frac{\bar{g}_{ib_i}(t)\ \bar{p}_i(t)}{\frac{1}{N_c}\sum_{k \neq i} \bar{g}_{kb_i}(t)\ \bar{p}_k(t) + \bar{\nu}_{b_i}(t)}. \tag{A.5}$$

Theoretical Interpretation of the Control Signals

In Equation (A.3) we disclosed the following general formulation of the C/I for the downlink

$$\bar{\gamma}_i(t) = \frac{\bar{g}_{ib_i}(t)\ \bar{p}_{b_i}(t)}{\sum_{k=1}^{M} \bar{g}_{ib_k}(t)\ \bar{p}_{b_k}(t)\ \theta_{ib_k} + \bar{\nu}_i(t)}, \tag{A.6}$$

and from Equation (A.4), we see that the formulation for the uplink is essentially analogous. From this expression it is instructive to relate to the assignments performed by a radio resource algorithm, which were listed in Section 2.5. Clearly the base station assignment corresponds to a choice of b_i's and the power control amounts to the choice of $\bar{p}_i$ and $\bar{p}_{b_i}$. Finally, the channel allocation or the choice of waveforms or codes is reflected by θ_{ij}.

Furthermore assume that the base stations and channels are assigned. Then we can define $\bar{h}_{ij}$ by

$$\bar{h}_{ij} = \bar{g}_{ib_j}\theta_{ib_j}.$$

Based on this definition, the C/I is given by a similar expression as in the orthogonal and single channel case in Equation (A.1). Therefore we can without loss of generality assume that the system is based on orthogonal signals and focus on a certain channel.

Appendix B

Reference

B.1 File

- **Load ...** Restore previous settings and results.
- **Save ...** Store settings and result.
- **Print ...** Brings up the `Print Dialog` window. Spools the chosen window (`MOSE`, `Simulation Results` or `Test Results` window) to printer or to file. The current settings of the simulator as well as date and time can be added to the output.
- **Clear** Resets the simulator, erases current simulation data, and restore default values.
- **Quick Start** Applies default settings and loads a specific configuration. See Section 4.2 for further details.
- **Quit** Clear data, and end session.

B.2 Setup

- **Network Configuration ...** Define the cell layout via the `Network Configuration` window:
  - Simulation Area (default 6×6 cells).
  - Wrap Around (default `enabled`).
  - Cell Radius (m) (default 1000m).
  - Antenna Type (default `Omnidirectional`).
- **MS Behaviour ...** Define the mobility behaviors. For further details, see Section 2.6.
- **MS Editor ...** Brings up the `MS Editor` control panel to configure and edit the location and behavior of the mobile stations.
  - `Move Mobile` Enables click-and-drag of mobiles.
  - `Add Mobile` Adds a new mobile. Drag to desired location and click to release.
  - `Set Behaviour` Enables change of behavior. Clink on mobile to toggle behavior
  - `Zoom` Enables zooming in the network.
- **Environment Parameters ...** Define the system parameters:
  - Noise level and type of noise (constant/Gaussian).
  - Path loss parameters, see Section 2.2.1.
  - Shadow fading parameters, see Section 2.2.2.
  - Time delays, see Section 3.1.1 (default `Power Outputs` one sample and no `Measurement` delay).
- **Controller Parameters ...** Define the controller parameters and feedback strategy (either previous computed or output power). For further details, see Sections 3.2 and 3.3.
- **Measurement Filters ...** Define the measurement filters. For further details, see Section 3.1.3.
- **Output Power Limitations ...** Define the output power limitations. For further details, see Section 3.1.2.

B.3 Simulation

- **Parameters ...** Defines the simulation parameters via a dialog window:
  - `Effects` Shadow fading, measurement filter and limitations are available (default `disabled`).
  - `Control Perspective` Either uplink or downlink is in focus (default `Uplink Power`).
  - `Simulation Time` Defines the sample interval and the number of samples to be simulated (default 0.5s and 20 samples respectively).
  - `Power Control Algorithm` See Sections 3.2 and 3.3.
  - `Initial BST Assignment` Assign the mobile station to the closest base station determined by either the least distance or attenuation.
  - `Handover Algorithm` See Section 2.6.
- **Simulation Control ...** Brings up the simulation control panel and disables some menus.
  - `Run` Runs the simulation in one piece.
  - `Step` Runs the next simulation step.
  - `Stop At ...` Runs the simulation and halts when reaching the specified time.
  - `Done` Ends simulation control session, and enables all the menus.
  - `Save State` Save the state of the previous simulation.
  - `Use State` Restore the random generators to saved state in order to repeat random sequences (default `disabled`).

B.4 Data Analysis

- **Performance Plots ...** Toggles the visibility of the `Simulation Results` window (default `disabled`).

B.5 Test Cases

- **Test Cases Setup ...** Brings up the `Test Definition` window, describing the predefined tests
  - `Sample Time Dependence`
  - `Feasibility`
  - `Gamma Distribution`
  - `Step Response` For further details, see Section 4.3.
- **Test Result Window ...** Toggles the visibility of the `Test Results` window (default `disabled`).

Bibliography

[1] J. Blom and F. Gunnarsson. *Power Control in Cellular Radio Systems.* Licenciate Thesis, Linköpings universitet, Sweden, June 1998. Available at `http://www.control.isy.liu.se`.

[2] L. Ahlin and J. Zander. *Principles of Wireless Communications.* Studentlitteratur, Lund, Sweden, second edition, 1998.

[3] G. A. Garrard. *Cellular Communications: Worldwide Market Development.* Artech House, Boston, MA, USA, 1998.

[4] W. C. Jakes. *Microwave mobile communications.* John Wiley & Sons, New York, NY, USA, 1974.

[5] W. C. Y. Lee. *Mobile Communications Engineering.* McGraw-Hill, 1982.

[6] T. S. Rappaport, editor. *Cellular Radio & Personal Communications*, volume 1. IEEE Press, Piscataway, NJ, USA, 1995.

[7] R. Steele. *Mobile Radio Communications.* Pentech Press, London, England, 1992.

[8] G. L. Stüber. *Principles of Mobile Communication.* Kluwer Academic Publisher, Boston, MA, USA, 1996.

[9] A. D. Kucar. Mobile radio: An overview. *IEEE Communications Magazine*, 29(11), 1991.

[10] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda. Field strength and its variability in VHF and UHF land-mobile radio service. *Review of the Electrical Communication Laboratory*, 16(9-10), 1968.

[11] M. Hata. Empirical formula for propagation loss in land mobile radio services. *IEEE Transactions on Vehicular Technology*, 29(3), 1980.

[12] M. Gudmundson. Correlation model for shadow fading in mobile radio systems. *IEE Electronics Letters*, 27(23), 1991.

[13] B. Sklar. Rayleigh fading channels in mobile digital communication systems. *IEEE Communications Magazine*, 35(7), 1997.

[14] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver Jr., and C. E. Wheatly. On the capacity of a cellular CDMA system. *IEEE Transactions on Vehicular Technology*, 40(2), 1991.

[15] J. Zander. Radio resource management in future wireless networks - requirements and limitations. *IEEE Communications Magazine*, 5(8), August 1997.

[16] J.M. Aein. Power balancing in systems employing frequency reuse. *COMSAT Technical Review*, 3(2), 1973.

[17] H. Alavi and R.W. Nettleton. Downstream power control for a spread spectrum cellular mobile radio system. In *Proc. IEEE Global Telecommunications Conference*, Miami, FL, USA, November 1982.

[18] R. W. Nettleton and Alavi H. Power control for a spread spectrum cellular mobile radio system. In *Proc. IEEE Vehicular Technology Conference*, Toronto, Canada, May 1983.

[19] R.W. Nettleton. Traffic theory and interference mangement for a spread-spectrum cellular radio system. In *Proc. ICC'80*, Seattle, WA, USA, June 1980.

[20] J. Zander. Performance of optimum transmitter power control in cellular radio systems. *IEEE Transactions on Vehicular Technology*, 41(1), February 1992.

[21] S. A. Grandhi, R. Vijayan, D. J. Goodman, and J. Zander. Centralized power control in cellular radio systems. *IEEE Transactions on Vehicular Technology*, 42(4), 1993.

[22] S. A. Grandhi, R. Vijayan, and D. J. Goodman. Distributed power control in cellular radio systems. *IEEE Transactions on Communications*, 42(2), 1994.

[23] J. Zander. Transmitter power control for co-channel interference management in cellular radio systems. In *Proc. WINLAB Workshop*, New Brunswick, NF, USA, October 1993.

[24] K. Åström and T. Hägglund. *PID Controllers: Theory, Design, and Tuning*. Instrument Society of America, Research Triangle Park, NC, USA, second edition, 1995.

[25] M. Almgren, H. Andersson, and K. Wallstedt. Power control in a cellular system. In *Proc. IEEE Vehicular Technology Conference*, Stockholm, Sweden, June 1994.

[26] R. D. Yates, S. Gupta, C. Rose, and S. Sohn. Soft dropping power control. In *Proc. IEEE Vehicular Technology Conference*, Phoenix, AZ, USA, May 1997.

Subject Index