Development of Resource Allocation Strategies Based on Cognitive Radio

Von der Fakultät für Elektrotechnik und Informatik
der Gottfried Wilhelm Leibniz Universität Hannover
zur Erlangung des Grades

Doktor der Naturwissenschaften
Dr. rer. nat.

genehmigte Dissertation
von

Dipl.- Math. Jamal Raiyn

geboren am 22/12/1969 in Haifa, Israel

2009

Referentin: Prof. Dr.-Ing. Helena Szczerbicka, Leibniz Universität Hannover, Germany

Referent: Prof. Dr. rer. nat. Jörg Hähner, Leibniz Universität Hannover, Germany

Tag der Promotion: 09.01.2009

Summary

The fourth generation of mobile communication aims to transmit not only voice and text but also videos and multimedia data. Furthermore, in the future it is expected to include web browsing, file transfer and database access. This requires wireless cellular networks to efficiently support packet data traffic. Therefore, the challenge in the design of wireless networks is to support both voice and packet data service of traffic with different quality of service parameters [93, 127]. On the other hand one aspect of this challenge is to develop an efficient scheme for assigning resources to new arriving calls or handoff of different traffic types. Since the blocking probability is one of the most important quality of service parameters, the quality of service of wireless cellular networks is often measured in terms of two probabilities. The first is the new call blocking probability so that a new call cannot be satisfied because of the unavailability of a proper free channel, and the second is the handoff blocking probability [117] that a proper free channel is not available when a mobile station wants to move into a neighboring cell. To meet this aspect of the challenge, this proposal offers a new assignment scheme based on cognitive radio (CR) to utilize frequency spectrum efficiently and to reduce call blocking probabilities. Cognitive radio offers new tools to manage the resource and to communicate efficiently avoiding interference in cellular systems.

Keywords: blocking probabilities, cognitive radio, handoff.

Zusammenfassung

Die vierte Generation der mobilen Kommunikation hat das Ziel, nicht nur Sprache und Text, sondern auch Multimedia Daten und Video zu übertragen. Des Weiteren ist für die Zukunft auch geplant, Webbrowser, Datenübertragung und Datenbankzugänge zu realisieren. Dazu werden effiziente, drahlose Netzwerke benötigt, welche Datentransfer unterstützen. Die Herausforderung besteht darin, drahtlose Netzwerke zu entwickeln, die Sprache und Daten mit unterschiedlichen QoS-Parametern unterstützen. Andererseits ist eine neue Kanal-Allokationsstrategie zu entwickeln, die die Call Blocking Probability reduziert. Um diese beiden (oben genannten) Voraussetzungen zu erfüllen, möchten wir eine neue, dynamische Methode zur Kanal-Allokation vorstellen, die auf Cognitive Radio basiert. Das Conginitve Radio Management bietet neue Werkzeuge, die zur Erhöhung der Spektrum Kapazität beitragen können.

Schlagworte: blocking probabilities, cognitive radio, handoff.

Declaration of Originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Fakultät für Elektrotechnik und Informatik at the Leibniz Universität Hannover.

Acknowledgements

I would like to express a sincere gratitude to my scientific advisor Professor Dr. Eng. Helena Szczerbicka for her guidance and encouragement throughout my doctoral work to develop independent thinking and research skills.

I would also like to express my gratitude to Dr. Avraham Freedmann from Hexagon Engineering Systems Company for his insightful comments. These comments have improved the quality of this thesis.

I would like to thank my parents and my family for their lifelong support. Last but not least, I would like to thank my wife and my two sons for their endless love and support, without which I would not have succeeded. And I dedicate my thesis to my family.

Contents

Introduction 11

1 Basic concepts in cellular networks 13

1.1 Frequency reuse 14
1.2 Cell splitting 17
1.3 Smart antennas 18
1.4 Antenna propagation 20
1.5 Cognitive radio 22
1.6 Handoff in the cellular systems 23

2 Channel allocation: state of the art 28

2.1 Open questions 32

3. Problem description 35

4. A new solution: Channel allocation based on CR 38

4.1 Channel model 40
4.2 Communication strategy 40
4.3 Distributor strategy 41
4.4 The structure of a cognitive radio scheme 44
4.5 Temporal reasoning strategy 45
4.6 Behavior rules of agents 47
4.7 Iterative swapping prediction (ISP) 48
4.8 Algorithm analysis 52
4.8.1 The delay calculation 52
4.8.2 The interference calculation 56
4.8.3 Identification of the interference source area 58
4.8.4 Identification of the interference victim area 59
4.8.5 Co-channel and adjacent channel reuse ratio probabilities in FCA 60
4.8.6 Co-channel and adjacent channel reuse ratio probabilities in DCA 60
4.8.7 Co-channel and adjacent channel reuse ratio probabilities in CR 61
4.8.8 Radio spectrum management 65
4.9 Handoff based on CR 72

5 Evaluation of cognitive radio approach 90

6 Conclusion and Future Work 93

Appendix A 95

Appendix B 103

Appendix C 106

References 107

List of Figures

Figure 1: Frequency reuse distance ... 16
Figure 2: Cell splitting ... 17
Figure 3: Physical MIMO channel ... 20
Figure 4: Handoff process ... 24
Figure 5: Basic idea ... 39
Figure 6: Message types ... 41
Figure 7: System architecture ... 41
Figure 8: Cognitive radio algorithm ... 44
Figure 9: Cognitive radio infrastructure ... 45
Figure 10: Cost function ... 46
Figure 11: Antenna propagation ... 50
Figure 12: Average received power ... 51
Figure 13: Channels distribution ... 51
Figure 14: Message complexity CR vs. DDCA ... 54
Figure 15: Channel acquisition time ... 56
Figure 16: Co-channel interference ... 59
Figure 17: Co-channel in the FCA ... 60
Figure 18: Co-channel in the DCA ... 61
Figure 19: Co-channel interference ... 63
Figure 20: Call blocking probabilities ... 64
Figure 21: Path loss with logarithmic scale ... 65
Figure 22: Path loss vs. distance ... 65
Figure 23: Resource control ... 66
Figure 24: Base station site ... 74
Figure 25: Base station deployment and frequency plan ... 75
Figure 26: Signal strength ... 75
Figure 27: Channel mutual interference ... 76
Figure 28: BS-MS interference ... 77
Figure 29: Handoff process ... 78
Figure 30: MS handoff ... 79
Figure 31: Handoff with sectorized antenna ... 80
Figure 32: Uplink actual E_b/N_0 (dB) ... 80
Figure 33: Handoff process based SNR ... 81
Figure 34: End-to-end delay ... 81
Figure 35: Comparison of two systems throughput ... 82
Figure 36: Bandwidth efficiency ... 83
Figure 37: Blocking probability ... 83
Figure 38: Heavy traffic loaded cell ... 84
Figure 39: Throughput under loaded cell ... 85
Figure 40: Number of the requested granted resources ... 86
Figure 41: Queuing delay ... 86
Figure 42: Handoff process of mobile stations ... 87
Figure 43: Critical zone ... 88
Figure 44: UE handoff pilot channel Ec/N0 (dB) ... 89
Figure 45: Total downlink throughput ... 89

Figure 46: Cell transmitted carrier power ... 89
Figure 47: A network model built in project editor ... 96
Figure 48: Node editor ... 97
Figure 49: Process model editor ... 98
Figure 50: Link model editor ... 98
Figure 51: Path editor ... 99
Figure 52: Packet editor ... 99
Figure 53: Probe editor ... 100
Figure 54: Simulation sequence editor ... 100
Figure 55: Analysis tool ... 101
Figure 56: Project editor workspace ... 101
Figure 57: Mean Square Error (dB) ... 103
Figure 58: OptiSite ... 104
Figure 59: NIR capability ... 105
Figure 60: Network planning ... 105

Glossary

3G	Third Generation
4G	Fourth Generation
ACI	Adjacent Channel Interference Ratio
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver Station
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CR	Cognitive Radio
DL	Downlink
DS	Direct Sequence
DSSS	Direct Sequence Spread Spectrum
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
GSM	Global System for Mobile Telecommunications
ME	Mobile Equipment (Domain)
MIMO	Multiple Input Multiple Output
MS	Mobile Station
MT	Mobile Termination/Terminal
QoS	Quality of Service
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RRC	Radio Resource Control
RSCP	Received Signal Code Power
SIP	Session Initiation Protocol
SIR	Signal to Interference Ratio
TDMA	Time Division Multiple Access
TD–CDMA	Time Division CDMA (hybrid TDMA–CDMA interface)
TDD	Time Division Duplex
TE	Terminal Equipment
TS	Time Slot
TPC	Transmission Power Control
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over IP

Introduction

Mobile wireless communication has turned to be a major means of voice communication (telephony). Nowadays it is becoming a viable solution to transfer data among mobile users who are on the move, introducing new mobile services like multimedia and real time data communications. This usage of such data services is expected to increase exponentially in the future. Cellular networks [39, 49, 57, 119, 137] divide the geographical area into smaller regions, called cells. Each cell has a mobile service station and a number of mobile terminals, which we call hosts. To establish a communication session (or call), a mobile host sends a request to the mobile service station in its cell. The session is supported if a wireless channel can be allocated for the communication between mobile host and the mobile service station. Since the frequency spectrum is limited, the frequency channels must be reused as much as possible in order to support the increasing demand for wireless communication [2, 75, 122, 126, 131]. A channel allocation algorithm consists of two parts: *a channel acquisition algorithm* and *a channel selection algorithm*. The *channel acquisition algorithm* is responsible for collecting information from other cells and making sure that two cells within D_{min} do not use the same channel. The *channel selection algorithm* is used to choose a channel from a large number of available channels in order to achieve better channel reuse. There are several types of channel selection algorithms [6, 12, 19, 21, 25, 32, 54-55, 82, 85, 87, 98, 147]. We distinguish between different channel allocation schemes. Fixed channel allocation [81] is the simplest channel assignment algorithm. In the fixed channel assignment strategy, the frequency channels assigned to a cell are fixed. In contrast to fixed channel allocation strategy, in the dynamic channel allocation strategy [79, 110] there is no fixed relationship between channels and cells in dynamic channel allocation. All channels are kept in a central pool and are assigned dynamically to radio cells as new calls arrive in the system. After a call is completed, its channel is returned to the central pool. Additionally, we make a distinction between centralized or decentralized algorithm [8, 44, 74, 78, 128, 140, 141] for resource assignment. As an example of the first, consider a network in which a central controller handles the requests for resources from all processes and only permits an acquisition, if it would not lead to deadlock. A decentralized algorithm would not use a central controller. Rather, each process would be equivalent, cooperating with neighbors to a common end. The procedure above describes the problems in terms of traditional voice only circuit switched cellular networks. Modern data communication systems have additional resources. For example power and time can also be considered as resources. An increase of transmission power [13, 57] enables the increase of data rate and subsequently shorter transmission time. On the other hand an increased transmission power causes more interference in neighboring cells. The proposed channel allocation schemes are developed and designed to deal with a specific problem that restrict to one generation mobile communication. The major goal of this thesis is to reduce the call blocking rate in cellular systems. The call blocking rate is caused by delay and interference. To meet this aspect of the challenge, we introduce in this thesis channel allocation scheme based on cognitive radio. The goal of the cognitive radio scheme is to achieve a high degree of channel usage and a low rate of call blocking in cellular systems. The cognitive radio scheme offers several features like autonomy and negotiation. The use of cognitive radio gives greater autonomy to the base stations. This autonomy allows an increase in flexibility to deal with new situations in traffic load. The negotiation is used to avoid conflict in resource allocation. In this thesis the cognitive radio schemes deal with the delay, the interference (co-channel and adjacent), and the repeated unnecessary handoff in the same cell.

The thesis is divided as follows:

- In the first chapters, we present some features of the cellular concept, such as frequency reuse, cell splitting and traffic engineering in mobile networks.
- In the second chapter, we will describe the main strategies of channel allocation that have been proposed to improve the performances of the cellular networks.
- In the third chapter, we introduce the major problem in cellular systems, how to handle a limited number of channels. Furthermore, we analyze the currently proposed channel allocation strategies to increase the utility of channels in cellular systems.
- In the fourth chapter we introduce a channel allocation scheme based on cognitive radio schemes. The goal of the cognitive radio scheme is to achieve a high degree of channel usage and a low rate of call blocking in cellular systems. The cognitive radio scheme offers several features that contribute to the increase of the channel capacity in cellular systems. The cognitive radio approach will handle the co-channel interference and the power control issues.
- In the fifth and sixth chapter we evaluate the cognitive radio scheme and we conclude and represent the work plan.

1 Basic concepts in cellular networks

The cellular concept [120] is a mobile network architecture composed ideally of hexagonal cells. The cells represent geographic areas. Inside the coverage area, the users, called *mobile stations* (MS) are able to communicate with the network while moving inside the cellular network. Each cell has a *base station* (BS), which serves the mobile stations. Base stations are linked to *a mobile switching centre* (MSC) also called *mobile telephone switching office* (MTSO) responsible for controlling the calls and acting as a gateway to other networks. The BS allocates network resources for the users within its cell for the communication to take place. The network resources are frequency channels in a first generation analog system [102], a combination of a channel and a time slot in second generation TDMA systems, like the GSM [57] and a code in CDMA systems selected for use in third generation mobile systems [98]. CDMA system [40, 47, 148] is considered today, one of the major cellular telecommunications technologies. The CDMA system was totally unlike any system used before. CDMA, which stands for “Code Division Multiple Access”, is different than those traditional ways in that it does not allocate frequency or time in user slots but gives the right to use both to all users simultaneously. To do this, it uses a technique known as *Spread Spectrum* [84, 89]. In effect, each user is assigned a code which spreads its signal bandwidth in such a way that only the same code can recover it at the receiver end. This method has the property that the unwanted signals with different codes get spread even more by the process, making them like noise to the receiver. We shall use the term “frequency channel” to refer to those resources, without loss of generality. When an active user (i.e. a mobile station using a frequency channel) reaches the boundary of the cell, it needs to change its current frequency channel for another belonging to the neighboring cell. This network procedure is known as *handoff* or *handover* [97]. The essential features of the cellular system that made the achievement of the above objectives were *frequency reuse* and *cell splitting* [84] possible. *Frequency reuse* refers to the use of the same frequency carrier in different areas that are distant enough so that the interference caused by the use of the same carrier is not a problem. The reason for the application of frequency reuse is twofold: Firstly to reduce the cost of the land transmitter/receiver site by placing several moderate power land sites to cover sub-areas (cells) of the designated area for use of the network operator [57]. Secondly to greatly increase the number of simultaneous calls that can be covered by the same number of allocated channel frequencies. *Cell splitting* is the reconfiguration of a cell into smaller cells.

This feature makes it possible for the same network to service different densities of demand for channels. Larger cells can serve low demand density areas and smaller cells high demand density areas. Cell splitting is a long-term configuration planning that allows the system to adjust to a growth in traffic demand in certain areas, or in the whole network, without any increase of the spectrum allocation.

1.1 Frequency reuse

The distribution of the frequency channels in a cellular network [56] is dependent on several parameters; such as cellular geometry, signal propagation characteristics [14] and signal interference. The assignment of frequency channels in the cellular concept is fixed, i.e. a set of frequency channels is statically assigned to a cell. This same set is reused in another cell distant enough to allow the use of the frequency channels with acceptable signal interference. Cells that use the same set of frequency channels are called *co-channel cells* and the distance between them is called *co-channel reuse distance* [59]. The total number of frequency carriers allocated to a network operator is divided in sets and each set is assigned to a cell inside a cluster of cells. The cluster of cells forms a pattern. The pattern is reused according to the co-channel reuse distance. The choice of the number of cells per cluster is mainly governed by co-channel interference considerations. The propagation path loss of a signal is a function of several factors, such as environment, antenna type, antenna height, location etc. considering omnidirectional antennas, the propagation path loss in an urban environment in 40 dB per decade, i.e. the signal will suffer a 40 dB each time the distance is increased by 10 [90]. The difference in power reception at two different distances d_1 and d_2 would be [57]:

$$\frac{C_1}{C_2} = \left(\frac{d_2}{d_1}\right)^{-4} \tag{1.1}$$

Where

- C_1 is the received carrier power at receiver 1.
- C_2 is the received carrier power at receiver 2.
- d_1 is the distance measured from the transmitter to receiver 1.
- d_2 is the distance measured from the transmitter to receiver 2.

Therefore, the signal strength is inversely proportional to the distance to the power 4 in decibel expression equation 1.2 becomes [57]:

$$\Delta C = 10\log\frac{C_2}{C_1} = 40\log\frac{d_1}{d_2} \tag{1.2}$$

Under the same conditions, but in free space, the propagation path loss would be of 20dB/decade. In a real mobile radio environment the propagation path loss [126] will vary as:

$$\Delta C = \alpha d^{-\gamma} \tag{1.3}$$

or in decibel:

$$\Delta C = 10\log\alpha - 10\gamma\log d \tag{1.4}$$

Where

- γ is the propagation path loss factor.
- α is a constant.
- d is the distance from the transmitter to the receiver.

The γ parameter usually lies between 2 and 5; it cannot be lower than 2, the free space condition. Co-channel interference occurs as a result of multiple uses of the same frequency carrier. The carrier-to-interference ratio (C/I) [119] is used to measure the amount of interference over a specified carrier.

$$\frac{C}{I} = \frac{C}{\sum_{k=1}^{K_I} I_k} \tag{1.5}$$

Where K_I is the number of co-channel cells interfering with the wanted (one) [90]. Assuming the local noise is much less than the interference level and can be neglected, the *C/I* in Equation 1.5 represent the working conditions of the receiver best. The worst case level of the *C/I* can be expressed by Equation 1.6:

$$\frac{C}{I} = \frac{R^{-\gamma}}{\sum_{k=1}^{K_L} D^{-\gamma} k} \tag{1.6}$$

Where γ is the propagation path loss factor. *D* is the frequency reuse distance, namely the distance to the closest interferer, assuming all K_L interferers are of that distance. *R* is the radius of the cell, defined as the distance from the centre of the cell to any of its vertices, representing the lowest possible wanted signal strength. The frequency reuse distance (*D/R*) [2] can be related to a finite set of cells *N* in a hexagonal cellular network. In [97, 100] a convenient set of co-ordinates for hexagonal geometry was introduced. The positive halves of two axes intersect at a 60-degree angle, and the unit distance along either axis is $\sqrt{3}$ times the radius of the cell (*R*) that corresponds to the distance between the centers of two hexagonal cells as illustrated in Figure 1. The distance between the origin to any cell centre is given by:

$$D = \sqrt{i^2 + ij + j^2} \tag{1.7}$$

The vectors from the centre of any arbitrary cell and the six adjacent cells are separated from each other by 60 degrees; the same observation is valid for the vectors from a cell to its co-channel cells. Therefore, a cluster of contiguous cells can be visualized as a large hexagon. It is not claimed that all kind of clusters will have a hexagon shape, but a large hexagon can have the same area as any valid cluster. As the distance between centers of adjacent cells is equal, the distance between centers of the large hexagon is $\sqrt{i^2 + ij + j^2}$. The pattern of large hexagons can be visualized as an enlarged replica of the original cellular pattern with a scale factor of $\sqrt{i^2 + ij + j^2}$. Therefore, the number of cell areas contained in the area of the large hexagon is:

$$N = i^2 + ij + j^2 \tag{1.8}$$

From equation (1.8), valid number of cells per cluster are 3,4,7,9,12,13,19 etc. Finally, the relation between the co-channel reuse distance (*D/R*) and the number of cells per cluster can be found by combining the equations 1.7 and 1.8 and replacing the unity by $\sqrt{3}R$:

$$D / R = \sqrt{3 * N} \tag{1.9}$$

Now, the minimum number of cells per cluster that is needed to meet the system performance requirements can be determined. When considering omnidirectional cell site and flat terrain, a cluster with 7 cells gives a 4.58 frequency reuse distance, enough to comply with performance requirements.

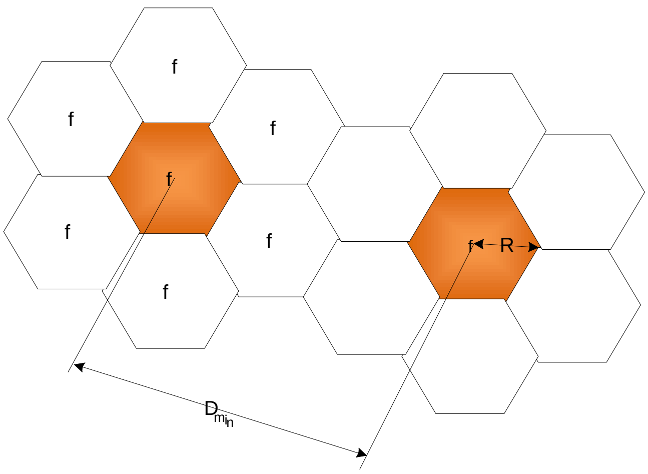


Figure 1: Frequency reuse distance

1.2 Cell splitting

Cell splitting, as described in Figure 2, allows the system to grow gradually in response to a growing demand of traffic. The main idea based on reducing the radius of a cell by half and splitting the old cell into a number of cells with different sizes. The goal behind cell splitting is that the reuse frequency can be used more often allowing the traffic to grow several times in the same area where an old cell was placed. Reusing the same frequency channel in different cells is allowed only if the co-channel interference constraints are satisfied between cells. Otherwise adjacent channel interferences occurs [62].

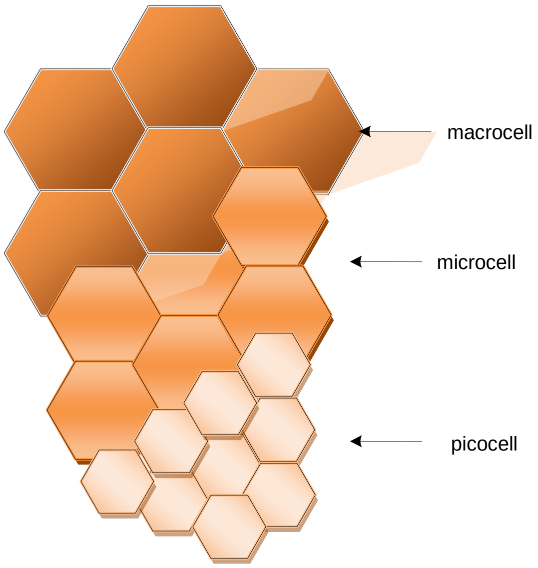


Figure 2: Cell splitting

In this section, we introduce the description of the difference between practical deployment and the hexagonal cell model:

- Coverage zones of cells are not hexagonal: the radio signal coverage must be guaranteed. The received signal strength must always be higher than a threshold according to the receiver sensitivity, and holes in the coverage area should be avoided. However, the coverage zones are not hexagonal in real radio networks.
- Cells are not equal in size and shape (as a result of the cell splitting process): in Practice, engineers draw hexagonal-shaped cells on a layout to simplify the planning and design of a cellular system because it approaches a circular shape that is the ideal coverage area of a base station. In real world, however, each cell varies depending on the radio environment. Due to constraints imposed by the natural and man-made

terrain, the real shape of cells is very irregular. Based on the size of cells, they can be classified as one of the following three types:

- Macrocells provide overall coverage, especially to fast-moving mobiles like those in cars. The base station antenna is mounted above the surrounding buildings, providing a cell radius from around 1 to 30 km.
- Microcells are used in areas with high subscriber density such as urban and suburban area. Base station antennas are placed at an elevation of street lamp, so the shape of microcells is defined by the street layout. The cell length is up to 2 km.
- Picocells are designed for very high mobile user density or high data rate applications, typically in indoor environments [65]. The radius of Picocells is between 10-200 m.

1.3 Smart antennas

Base station antennas have conventionally been omnidirectional or sectored [27] and most of the transmission power is radiated in other directions than toward a specific user. In addition, the power radiated in other directions will be experienced as interference by other users. The main idea of smart antennas [53, 70, 92] is to use base station antenna patterns that are not fixed but adapt to the current radio conditions. This can be visualized as the antenna directing a beam toward the communication partner only. The difference between the fixed and the smart antenna concept, the smart antennas will lead to a much more efficient use of the power and spectrum [91], increasing the useful received power, as well as reducing interference. Several different definitions for smart antennas are used in the literature. Normally, the term “antenna” comprises only the mechanical construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable and vice versa. We may call it *the radiating element*. In the context of smart antennas, the term “antenna” has an extended meaning. It consists of a number of radiating elements, a combining/ dividing network and a control unit. The control unit can be called the smart antenna’s intelligence, normally realized using a digital signal processor (DSP). The processor controls feeder parameters of the antennas, based on several inputs, in order to optimize the communications link. Based on the definition above, one can define “levels of intelligence” as follows:

- Switched lobe (SL): this is called switched beam. It is the simplest technique and comprises only a basic switching function between separate directive antennas or predefined beams of an array.
- Dynamically phased array (PA): by including a direction of arrival (DoA) algorithm for the signal received from the user, continuous tracking can be achieved and it can be seen as a generalization of the switched lobe concept.
- Adaptive array (AA): in this case, a DoA algorithm for determining the direction toward interference sources (e.g., other users) is added. The radiation pattern can then be adjusted to null out the interference. In addition, by using special algorithms and space diversity techniques, the radiation pattern can be adapted to receive multipath signals which can be combined. These techniques will maximize the signal to interference ratio (SIR).
- MIMO systems [125, 129] that can use multiple antenna arrays to increase transmission capacity. MIMO refers to radio links with multiple antennas at the transmitter and the receiver side. Given multiple antennas, the spatial dimension can be exploited to improve the performance of the wireless link. The performance is often measured as the average bit rate (bit/s), the wireless link can provide or as the average bit error rate (BER). Multiple-Input Multiple-Output (MIMO) describes systems that use more than one radio and antenna system at each end of the wireless link. In the past, it was too costly to incorporate multiple antennas and radios in a subscriber terminal. Recent advances in radio miniaturization and integration technology now makes it feasible and cost effective. Combining two or more received signals has the most immediate benefit of improving received signal strength, but MIMO also enables transmission of parallel data streams for greater throughput. For example, in a 2 x 2 MIMO (two transmit and two receive elements) dual polarization point-to-point system, the carrier's allocated frequency can be used twice, doubling the throughput data rate effectively. In point-to-multipoint systems using MIMO, each base station antenna transmits a different data stream and each subscriber terminal receives various components of the transmitted signals with each of its subscriber antennas as Figure 3 illustrates. By using appropriate algorithms, the subscriber terminal is able to separate and decode the parallel simultaneously received data streams. The mobile WiMAX standard covers a suite of MIMO encoding techniques for up to four antennas at each end of the link, (4 x 4 MIMO).

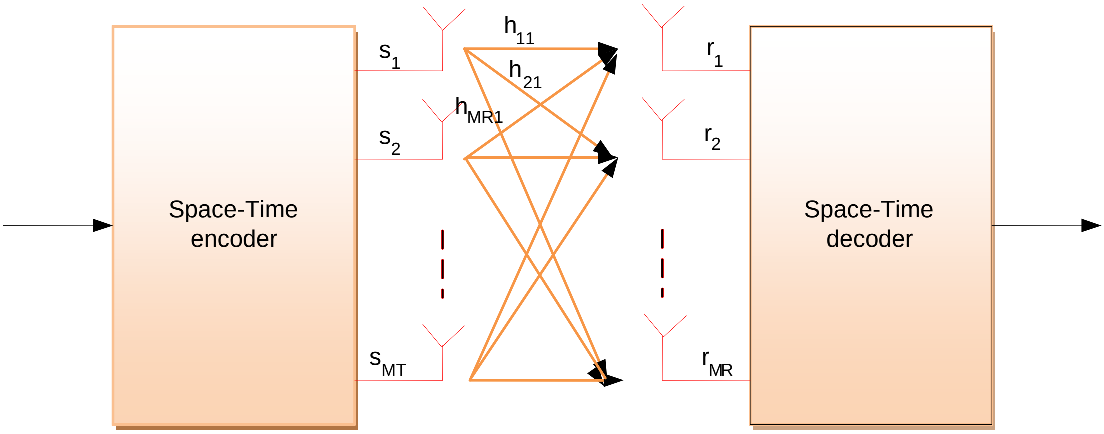


Figure 3: Physical MIMO channel

1.4 Antenna propagation

When the signal propagates [5, 14-17, 45, 61, 69, 112, 129] from the transmitter to the receiver it will become distorted and attenuated. The channel path loss model described will give a view on how the average large-scale signal changes with the distance.

A. Free Space Propagation

In most environments, it is observed that the radio signal strength falls as some power α of the distance, called the power-distance gradient or path-loss gradient. That is, if the transmitted power is P_t, after a distance d in meters, the signal strength will be proportional to $P_t d^{-\alpha}$. In its most simple case, the signal strength falls as the square of the distance in free space (α = 2). When an antenna radiates a signal, the signal propagates in all directions [1]. The signal strength density at a sphere of radius d is the total radiated signal strength divided by the area of the sphere, which is $4\pi d^2$. Depending on the radio frequency, there are additional losses, and in general, the relationship between the transmitted power P_t and the received power P_r in free space is given by [15]:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \tag{1.10}$$

Here G_t and G_r are the transmitter and receiver antenna gains respectively in the direction from the transmitter to the receiver; d is the distance between the transmitter and receiver; $\lambda = c/f$ is the wavelength of the carrier; c is the speed of the light in free space (3×10^8 m/s); and f is the frequency of the radio carrier. If we let $P_0 = P_t G_t G_r (\lambda/4\pi)^2$ be the received signal strength at the first meter (d = 1m) [56], we can rewrite this equation as:

$$P_r = \left(\frac{P_0}{d^2} \right) \tag{1.11}$$

In decibels (dB), this equation takes the form [56]

$$10\log_{10}(P_r) = 10\log_{10}(P_0) - 20\log_{10}(d) \tag{1.12}$$

B. Shadow Fading

The simplest method of relating the received signal power to the distance is to state that the received signal power P_r is proportional to the distance between transmitter and receiver d, raised to a certain exponent α, which is referred to as the distance-power gradient [16], that is

$$P_r = P_0 d^{-\alpha} \tag{1.13}$$

where P_0 is the received power at a reference distance (usually one meter) from the transmitter. For free-space, as already discussed, $\alpha = 2$, and for simplified two-path model of an urban radio channel, $\alpha = 4$. For indoor and urban radio channels, the distance-power relationship will change with the building and street layout, as well as with construction materials and height of the buildings in the area. Generally, variations in the value-power gradient in different outdoor areas are smaller than variations observed in indoor areas. The results of indoor radio propagation studies [42] show value of α smaller than 2 for corridors or large open indoor areas and values as high 6 for metallic buildings. The distance-power relationship of the equation (1.15) in decibels is given by

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d) \tag{1.14}$$

where P_r and P_t are the received signal strengths at d meters respectively. The last term in the right-hand side of the equation represents the power loss in dB with respect to the received power at one meter, and it indicates that for a one-decade increase in distance the power loss is 10α dB and for one-octave increase in distance it is 3α dB. If we define the path loss in dB at a distance of one meter as $L_0 = 10log_{10}(P_t)-10log_{10}(P_0)$, the total path loss L_p in dB is given by:

$$L_p = L_0 + 10\alpha\log(d) \tag{1.15}$$

This presents the total path-loss as the path-loss in the first meter plus the loss relative to the power received at one meter. The received power in dB is the transmitted power in dB minus the total path loss L_p. This equation is used in the literature [56] to present the distance-power relationship.

1.5 Cognitive radio

Simon Haykin defines a cognitive radio (CR) as [66]: "An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind:

i. Highly reliable communications whenever and wherever needed;
ii. Efficient utilization of the radio spectrum.

Coming from a background where regulations focus on the operation of transmitters, the FCC has defined a cognitive radio as [48]: "A radio that can change its transmitter parameters based on interaction with the environment in which it operates." Meanwhile, the other primary spectrum regulatory body in the US, the NTIA [34], adopted the following definition of cognitive radio that focuses on some of the applications of cognitive radio: "A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, and access secondary markets." The international spectrum regulatory community in the context of the ITU Wp8A working document is currently working towards a definition of cognitive radio that focuses on capabilities as follows: "A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly." While aiding the FCC in its efforts to define cognitive radio, IEEE USA [76] offered the following definition [43]: "A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users." The broader IEEE tasked the IEEE 1900.1 group to define cognitive radio which has the following working definition [43]: "A type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters." Likewise, the

SDR Forum participated in the FCC's efforts to define cognitive radio and established two groups [33] focused on cognitive radio. The Cognitive Radio Working Group focused on identifying enabling technologies uses the following definition: *"A radio that has, in some sense, (1) awareness of changes in its environment and (2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimize a loss in performance."*

However, the SDR Forum Special Interest Group for Cognitive Radio, which is developing cognitive radio applications, uses the following definition: *"An adaptive, multi-dimensionally aware, autonomous radio (system) that learns from its experiences to reason, plan, and decide future actions to meet user needs."*

Finally, the author of this text participates in the Virginia Tech Cognitive Radio Working Group which has adopted the following capability- focused definition of cognitive radio [33]: *"An adaptive radio that is capable of the following:*

i. awareness of its environment and its own capabilities,
ii. goal driven autonomous operation,
iii. understanding or learning how its actions impact its goal,
iv. recalling and correlating past actions, environments, and performance."

Finally, the following are some general capabilities found in all of the definitions:

i. observation: whether directly or indirectly, the radio is capable of acquiring information about its operating environment.
ii. adaptibility: the radio is capable of changing its waveform.
iii. intelligence: the radio is capable of applying information towards a purposeful goal.

1.6 Handoff in the cellular systems

Handoff is a basic mobile network capability for dynamic support of terminal migration. Handoff Management [22, 135, 142] is the process of initiating and ensuring a seamless and lossless handoff of a mobile terminal from the region covered by one base station to another base station. Analysis and studies show that the handoff process by splitting it into three main sequential phases: Detection, Search and Execution. The detection phase is the discovery of the need for the handoff. The search phase covers the acquisition of the information needed to perform the handoff. Finally, the handoff is performed during the execution phase. We make distinguish two types of handoffs:

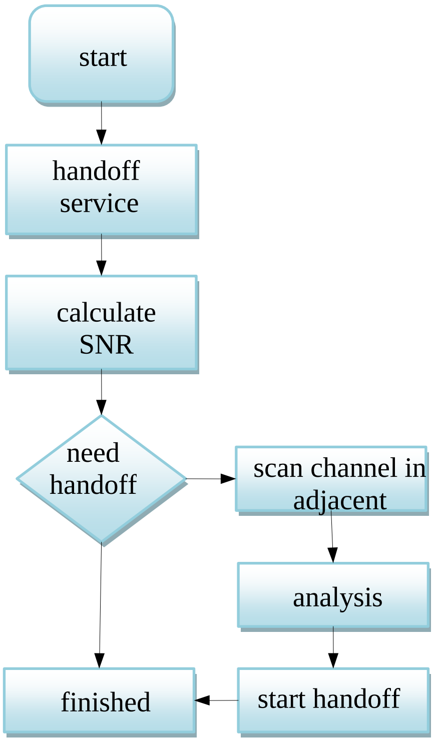


Figure 4: Handoff process

i. Vertical handoff

The handoff is called vertical, when the handoff and the mobility occur among heterogeneous networks.

ii. Horizontal handoff

The handoff is called horizontal, when the handoff happened in the same networks.

A. Handoff in various cellular systems

- **Handoff in GSM**

The global system for mobile communication (GSM) [57] is the most popular standard for mobile phone and it is considered a second generation (2G) mobile phone system. In GSM, there are two basic types of handoffs.

i. Internal Handoff:

   a. Intra-Cell handoff: In intra-cell handoffs, a call is transferred from one channel to another within the same cell. (re-allocation)

   b. Inter-Cell handoff: In inter-cell handoffs, a call is transferred from one cell to another, both of which are under the control of the same Base Station Controller (BSC).

ii. External Handoff:

a. Intra-MSC handoff: In intra-MSC handoff, the calls are transferred between different BSCs, but belonging to the same Mobile Services Switching Centre (MSC).

b. Inter-MSC handoff: In inter-MSC handoff, the calls are transferred between different MSCs. The old MSC is usually referred to as the anchor MSC and the new MSC is referred to as the relay MSC.

Handoffs are initiated by the mobile or the MSC. The GSM mobiles use TDMA to scan the "broadcast control channel" of up to 16 neighbouring nodes and create a list of 6 best cells for handoff. The decision is based on the signal strength. The GSM uses two handoff algorithms:

i. Minimum acceptable performance: In this algorithm, power control is given precedence over handoffs.

ii. Power Budget algorithms: In this algorithm, handoffs are initiated to maintain acceptable signal strengths and power levels.

A GSM system partitions the handoff tasks and localizes the handoff traffic with respect to the locality and the type of migration.

- **Handoff in UMTS**

The Universal Mobile Telecommunication System (UMTS) is considered a third generation (3G) mobile phone system [20, 101, 105, 116, 138, 150]. The handoff control of the Universal Mobile Telecommunication System (UMTS) terrestrial radio access network supports different types of handoffs and handoff procedures:

i. Intra-system Handoff, which can be further subdivided into:

a. Intra-frequency HO, between cells belonging to the same WCDMA carrier.

b. Inter-frequency HO, between cells operating on different WCDMA carriers.

ii. Inter-system HO between cells belonging to two different radio access technologies (e.g. UMTS and GSM/EDGE) or two different radio access modes (e.g. FDD/WCDMA and TDD/TD-CDMA)

UMTS supports both hard handoff and soft handoff procedures. For soft HO the cells are partitioned into the "Active set", which include all the cells currently participating in a soft HO connection of a terminal, and the "Neighbour Set"/ "Monitored Set" which include all cells currently monitored by the terminal. The mobile continuously measures serving and neighbouring cells, as indicated by the Radio Network Controller (RNC) and sends the measurements to the RNC. Soft HO is decided by the RNC. This is therefore a Mobile Evaluated HO, which instructs the Mobile to include or remove cells form its active set. In case the handoff is to be made to a different RNC and soft HO cannot be executed or not allowed, intra-frequency hard HO is performed. This procedure is also a Mobile Evaluated HO. Inter-frequency handoff is a handoff between different WCDMA carriers. It can be performed when two cells use different carriers, and it is also useful for a multi-layered (multi-tier) system. Inter-frequency HO is a network evaluated HO. When a mobile station is located where an Inter-frequency HO is possible and needed, the RNC commands the mobile to perform inter-frequency measurements and to report the results periodically. The HO decision is made at the RNC. Inter-system HO is a necessary feature to support upgrade of 2G systems to UMTS and also to support the different UMTS mode. Obviously the mobile station has to support both modes. The Inter-System HO is Network Evaluated; the mobile terminal must also support the necessary measurements. Inter-frequency and inter-system measurements require the mobile terminal measuring on a different frequency. If another receiver is to be avoided, this measurement can be done by stopping the normal transmission and reception for a certain period allowing the mobile terminal to measure on the other frequency. To achieve this gap without losing any data the data sent can be compressed in time, i.e. transmission and reception enter a Compressed Mode. There are three methods of generating the gaps to use the compressed mode:

- reducing the data rate used in the upper layers
- reducing the symbol rate used in the physical layer
- spreading factor splitting.

The standards allow CM to be applied in one direction only or in both directions simultaneously.

- **Handoff in WiMAX**

The Worldwide Interoperability for Microwave Access (WiMAX) is a telecommunications technology that provides wireless data in a variety of ways, from point-to-point links to full mobile cellular type access. WiMAX is considered a fourth generation (4G) mobile phone system. The mobile WiMAX standard [28] supports three physical-layer handoff mechanisms:

i. Hard Handoff – this is a 'break before make' handoff in which the subscriber terminal is disconnected from one base station before connecting to the next base station.
ii. Fast base station switching (FBSS) – the network hands-off the subscriber between base stations while the connection with the core network remains with the original base station.
iii. Macro-diversity handoff (MDHO) – the subscriber maintains a simultaneous connection with two or more base stations for a seamless handoff to the base station with the highest quality connection.

Hard Handoff is the most bandwidth-efficient and is mandated by WiMAX Forum profiles, while FBSS and MDHO are optional handoff modes. In addition to physical-layer handoffs, the overall end-to-end network infrastructure must support the processes of inter-network and inter-vendor handoff to ensure the continuity of the ongoing session, security and authentication, QoS provisioning, and billing. The WiMAX Forum's networking working group (NWG) has defined the end-to-end network as an all IP network to make handoff and service continuity easy to implement and use.

2 Channel allocation: state of the art

Numerous strategies have been proposed to deal with channel allocation [19, 26, 59, 94, 124, 134] in cellular systems. In this section, we present and discuss the channel allocation strategies. Generally, the channel allocation schemes [23, 30, 36, 50, 81, 83, 108, 123, 145, 139] can be divided into main four categories as follows,

i. Fixed channel allocation (FCA),

ii. Dynamic channel allocation (DCA),

iii. Hybrid channel allocation (HCA),

iv. Flexible channel allocation (FLCA).

In the fixed channel allocation [81], a set of channels is permanently allocated to each cell of the system. When a user requests a channel for communication, it searches the free channel in its own cell. If a free channel is available, it will be assigned to the user otherwise, the request will be blocked. In fixed channel allocation schemes, as soon as all the assigned channels in a cell are not free, no more traffic can be served in the cell even though there may be idle channels in the neighboring cells. The major deficiency of the fixed channel allocation strategy is that it cannot accommodate spatial and temporal traffic variations efficiently. Many borrowing schemes [81] were proposed later by relaxing the channel allocation rule in the basic fixed scheme. In these schemes, a channel can be borrowed by the neighboring cells, if it is idle and the reuse criterion is still satisfied. General in a channel borrowing scheme, an acceptor cell that has used all its nominal channels can borrow free channels from its neighbor cells (donors) to accommodate new cells. A channel can be borrowed by a cell if the borrowed channel does not interfere with exiting calls. When a channel is borrowed, several other cells are prohibited from using it. This is called channel blocking. Channel borrowing strategies deal with short-term allocation of borrowed channels to cells. Once a call is completed, the borrowed channel is returned to its nominal cell. The proposed channel borrowing schemes differ in the way a free channel is selected from a donor cell to be borrowed by an acceptor cell. The channel borrowing schemes can be divided into *simple* and *hybrid*. In the simple borrowing strategy, a nominal channel set is assigned to a cell, as in the fixed channel allocation case. After all nominal channels are used, an available channel from a neighboring cell is borrowed. To be an available channel for borrowing, the channel must not interfere with exiting calls. Although channel borrowing can reduce call blocking, it can cause interference in the donor cells in these cells from being completed. The simple borrowing strategy gives lower blocking probability than static fixed channel allocation under light and moderate traffic. However static fixed channel allocation performs better under heavy traffic conditions. This is due to the fact that in light and moderate traffic conditions, borrowing of channels provides the means to serve the fluctuations of offered traffic, and as long as the traffic intensity is low, the number of donor cells is small. In heavy traffic, the channel borrowing may proliferate to such an extent, due to channel locking, that the channel usage efficiency drops drastically, causing an increase in blocking probability and a decrease in channel utilization. In hybrid channel borrowing strategies, the set of channels assigned to each cell is divided into two subsets: A (local channels) and B (borrowable channels). Subset A is for use only in the nominally assigned cell, while subset B is allowed to be lent to neighbor cells. The ratio $|A|:|B|$ is determined a priori, depending on an estimation of the traffic conditions, and can be adapted dynamically in a scheduled or predictive manner. In *dynamic channel allocation schemes* [88, 79, 35, 106] implies that channels are allocated dynamically as new calls arrive in the system and is achieved by keeping all free channel in a central pool. After a call is completed, its channel returns to the central pool. In other words, with the dynamic channel allocation strategies, a cell may use any channel that will not cause channel interference. Typically, each channel is associated with a priority; when a cell needs a channel, it picks the available channel which has the highest priority. Thus, various dynamic channel schemes differ from each other in the way priorities are assigned to channels. There are three ways to assign channel priorities: *static*, *dynamic*, and *hybrid*. In a static-priority strategy such as the geometric strategy [11], each channel in each cell is assigned a fixed priority that does not change over time. In a dynamic-priority strategy such as the two-step strategy [42], the channel priority is dynamically computed. A hybrid-priority scheme [147] is something in between: the channel priority is calculated as a static base-priority plus a dynamic adaptive-priority. In the geometric strategy [11] each cell is assigned some channels as primary (local) channels based on a priori. These primary channels are prioritized. During a channel acquisition, a cell acquires the available primary channel that has the highest priority. If none of the primary channels are available, the cell borrows a channel from its neighbors according to some fixed priority assignment approach. When a cell acquires a channel, it always acquires the channel with highest priority. When a cell releases a channel, it releases the channel with the lowest priority. *The dynamic channel allocation schemes* can be classified into two categories: *centralized* dynamic channel allocation (CDCA) and *distributed* dynamic channel allocation (DDCA) [4, 31, 37, 60, 107, 115, 143]. In centralized dynamic channel allocation schemes [119], a channel is selected for a new call from a central pool of free channels, and a specific characterizing function is used to select one among many available free channels. The simplest scheme is to select the first available free channel that can satisfy the reuse distance. In addition, that free channel can be picked which can minimize the further blocking probability in the neighborhood of the cell that needs an additional channel. Centralized schemes can theoretically provide near optimal performance, but the amount of computation and communication among base stations lead to excessive system latencies and make them impractical. Furthermore, all these algorithms depend on a mobile switching center (MSC) to accomplish channel acquisition, which are referred to as centralized channel assignment algorithms. In other words, each cell notifies the MSC when it acquires or releases a channel so that the MSC knows which channels are available in each cell at any time and assigns channels to cells accordingly. The distributed dynamic channel allocation Schemes have been proposed that involve scattering of channels across a network. A channel is selected for a new call from its cell or interfering neighbor cells. The distributed dynamic channel allocation schemes have received considerable attention because of high reliability and scalability. In distributed channel allocation strategies, a mobile service station in cell communicates with other mobile stations directly to find the available channels and to make sure that assigning a channel does not cause interference with others cells. In general, there are two main approaches to design distributed channel allocation algorithms: *search* and *update*. In the search approach, when a cell needs a channel, it searches all neighboring cells to find the set of currently available channels and then picks one according to the channel selection strategy. In update approach, a cell maintains information about available channels. When a cell needs a channel, it selects an available channel according to the underlying channel selection strategy and consults the neighboring cells whether it can acquire the selected channel or not. Also, a cell informs its neighbors each time it acquires or releases a channel, so that each cell has up-to-date information on the available channels. *The hybrid channel allocation schemes* [10, 110] are a mixture of the fixed channel allocation a dynamic channel allocation techniques. In hybrid channel allocation, the total number of channels available for service is divided into fixed and dynamic sets, which means few channels are permanently allocated to each cell and the remaining channels are allocated dynamically. The performances of the hybrid channel allocation schemes are intermediate between fixed and dynamic channel allocation schemes. In the *flexible channel allocation* (FLCA) schemes [125], the set of available channels is divided into fixed and flexible sets. Each cell is assigned a set of fixed channels that typically suffices under a light traffic load. The flexible channels are assigned to those channels that have become inadequate under increasing traffic loads. The assignment of these emergency channels among the cells is done in either a scheduled or predictive manner. In the literature proposed FLCA techniques differ according to the time at which and the basis on which additional channels are assigned. In the predictive strategy, the traffic intensity or, equivalently the blocking probability is constantly measured at every cell site so that reallocation of the flexible channels can be carried at any point in time. Fixed and flexible channels are determined and assigned (or released) to (or from) each cell according to the change in traffic intensity or blocking probability measured in each cell. The number of dynamic channels required in a cell is determined according to the increase in measured traffic intensity. The acquired flexible channels can be used in a manner identical to the fixed channels. As long as a cell has several free fixed channels, no flexible channels are assigned to it if the traffic intensity is below a certain threshold. Recently, some proposed channel allocations have introduced the use of the intelligent agent in mobile networks. The first work on using intelligent agents to control mobile networks was introduced by E. L. Bodanese [18]. The proposed scheme based on intelligent agent aimed to improve the acquisition of radio resource in congested macro-cells where base stations are not able to share information by interference measurements, but only by explicit exchange of information. This resulted in a distributed resource allocation scheme for second generation mobile networks using intelligent agents that offered an efficient solution for resource allocation under moderate and heavy loads. However, in that work, the author restricted herself to channel assignment in macro-cells and for voice communication in second generation networks. The author used the message exchange to update the intelligent agent without to take into consideration the delay that is caused by message exchange. Furthermore, it does not deal the main problems in the cellular system like call blocking rate in the handoff process, repeated unnecessary Handoff, and SNR. The proposed algorithm has been compared to fixed channel allocation.

2.1 Open questions

In this section, we will discuss and analyze the channel allocation schemes in cellular systems. Many studies have shown [10, 147] that the major deficiency of the fixed channel allocation scheme is that it cannot accommodate spatial and temporal traffic variations efficiently. Because as soon as all the assigned channels in a cell are busy, no more traffic in the cell can be served even though there may be idle channels in the neighboring cells. The centralized dynamic channel may achieve the near optimum performance in whole system: the maximum capacity or minimum blocking probability with certain interference level. However, as the number of cells increases, the centralized computation may become mathematically intractable. The method is also impractical under highly varying traffic because of the difficulty in measuring the actual condition. In addition, the measurement and transmission of current local state information and control instruction may occupy some spectrum resource and cause a large penalty in system capacity. We conclude that the centralized control is impractical for implementation because it requires system-wide information and the complexity of searching all possible reallocations is computationally hard. The distributed dynamic channel allocation schemes (DDCA) use either local information about the current available channels in the cell's vicinity (cell based) or signal strength measurements. In cell-based schemes, a channel is allocated to a call by the base station at which the call is initiated. The difference with the centralized approach is that each base station keeps information about the current available channels in its vicinity. The channel pattern information is updated by exchanging status information based messages between base stations. The deficiency of the distributed schemes is that the higher messages exchange may cause delay in the system. In the case that the base station is busy and searching for a free available channel, it will put the received message in the queue. An increasing in response time causes an increasing the call blocking rate, too. In addition, It can be occurred that the delayed message includes false information about the state resource allocation in the base station. Hence, the two base stations allocate the same channel to two mobile stations, which will cause interference. Furthermore, if the DDCA requires a lot of processing and complete knowledge of the state of the entire system, the call setup delay would be significantly long without high-speed computing and signaling. The delay in cellular systems is considered as the main reason limiting the capacity and increasing the handoff call blocking probability. We note that in some application fields like real-time communication it is necessary to ensure a seamless and lossless handoff. In distributed dynamic channel allocation, each base station transmits signals, and a mobile station selects the base station with the strongest received power. This kind of method will take place repeated or unnecessary handoff, and it increases the delay in the cellular systems. All those channel assignment schemes mentioned above for increasing the spectral efficiency are assuming homogenous hexagonal cells. Several developed assignment schemes have improved the performance of the fixed channel assignment strategy for traffic densities over different traffic load conditions. However, most of the solutions proposed have an entirely reactive approach: the response to a series of events follows an algorithm that is designed to react to a specific situation, this limits their efficiency. Furthermore, the allocation schemes focus on the channel assignment problem central to the second generation mobile communications. However, these strategies offer neither optimal solution nor handle the new mobile generations and their quality of service requirements. Most of the current channel allocation strategies focus on circuit-switched voice communication, but can have low performance for multimedia, broadband communication. In this work, we will study the channel assignment problem by considering a realistic cellular mobile system with *uniform traffic environment* [103], which means, an equal number of channels can be found in the channel set for each cell. In uniform traffic environment the traffic condition is not varying with time, which means approximately the same number of call request will arrive in each cell. Other is called *non-uniform traffic environments*. In non-uniform traffic environments some cells are heavily loaded. Heavily loaded cells are evenly over the region, and have call arrival rates higher than the lightly loaded cells. Therefore all the allocation schemes that have been introduced, did not take the effect of *handoffs* (neither horizontal nor vertical handoff) into account in the performance of the system. This caused a high call blocking rate in the cellular systems. Focusing on the main points mentioned above, and in order to overcome the disadvantage of FCA, CDCA, DDCA methods, and to meet the new generation mobile communication service requirements, we introduce the cognitive radio scheme. The use of the cognitive radio in a cellular system will give greater *autonomy* to base stations. This autonomy allows an increase in flexibility to deal with new situations in traffic load and in non-regular networks as well as a decrease in the information load on the network. This increases the *robustness* of the network as a whole, distributing the knowledge and allowing *negotiation* when conflict occurs. Furthermore, we note that the utilization of some licensed spectrum is always low. In order to increase the spectrum utilization, the cognitive radio scheme is suggested for unlicensed users to access the spectrum unoccupied by the licensed users. With introducing the cognitive radio scheme, we will handle the co-channel interference, power control, and the handoff process. Compared to distributed dynamic channel allocation, we expect from the use of the channel allocation based on cognitive radio scheme to reduce the interference, delay, and the repeated unnecessary handoff process in the same cell.

3. Problem description

Over the last two decades, the demand for mobile host and multimedia services increased rapidly. One of the biggest challenges in supporting multimedia applications in cellular systems is to fulfill the mobile user demand and satisfy his preferences under the constraint of the limited radio bandwidth, and to utilize the limited *spectrum availability* to meet the increasing demand for mobile service. Some of the most often used methods to increase the spectral efficiency are *resource allocation schemes*. Various channel allocation schemes have been introduced to provide Quality of Service (QoS) [40, 127, 148] and efficient channel utilization in cellular networks. There are many parameters to measure the QoS of a network.

These include throughput, latency, service availability etc. The blocking probability is one of the most important QoS parameters. Since users are mobile, the QoS of wireless networks are often measured in terms of two probabilities: the new arriving *call blocking probability* and the *handoff blocking probability*. Hence, this research deals with the main issue:

How to allocate resources (e.g. frequency channels) to radio ports of a wireless system (e.g. cells in a cellular mobile network) that can improve the traffic performance of network (e.g. lower blocking probability in voice networks, lower latency in data networks etc.)?

In general, we assume that the resources in cellular network are distributed over *m* different cells (or BS) and are to be allocated to *n activities*. Activity *j* corresponds to the cell's request for the resource and the base station controller decides whether requests are granted or not. The base station controller is an agent that manages the cell. Let R_j denote the total amount of the resource that activity *j* requires in a cellular system. Among R_j, let us assume that activity *j* requests $x_{i,j}$ amount of the resource from cell_i. $x_{i,j}$ represents activity *j*'s demand for the resource at cell_i. Since activity *j*'s total demand for the resource is R_j, the following equation holds:

$$\sum_{i=1}^{m} x_{i,j} = R_j , \quad (1 \le j \le n). \tag{3.1}$$

Let N_i denote the total amount of the resource at cell_i. Furthermore, we assume that N_i is constant. Since the total demand at cell_i is smaller than N_i, the following equation holds:

$$\sum_{j=1}^{n} x_{i,j} \le N_i , \quad (1 \le i \le m) \tag{3.2}$$

In other words, we assume that the resource requests are always granted, and the requested amounts of resource requests are always granted. Furthermore, the demand for the resource at $cell_i$, $x_{i,j}$, also represents the amount actually allocated. In the modern data communication systems, we consider the power transmission as the resources. An increase of transmission power enables the increase of data rate and subsequently shorter transmission time. On the other hand, an increased transmission power causes more interference in neighboring cells. One of the physical measures of RF channel quality is the *carrier-to-interference* or *CIR*. This ratio is logarithmically proportional to the signal quality enjoyed by the receiver of the signal. The larger the *C/I* ratio, the better the channel quality is. If the measured *C/I* falls below a certain level, CIR_{min}, which depends on system type and operator requirements, the mobile should be in the coverage region of another cell and a call handoff should be performed. The interior of the cell should provide *C/I* ratio which exceed this level, unless the mobile is located in an RF coverage "hole." In general, for a feasible solution for the resource managements in the cellular systems must be satisfied four requirements as follows:

- Coverage requirement: each of the MS locations must be able to connect at least to one base station and the received signal strength must exceed a given level P_{min}.
- Transmitter power requirements: the transmitted power of the mobile stations in the system must not exceed a maximum level P_{max}.
- Downlink SIR requirement: each downlink SIR must exceed a threshold of SIR^{th}.
- Uplink SIR's requirement: each uplink SIR must exceed a threshold of SIR^{th}.

In this case, we consider the problem of minimizing total transmitter power. To minimize the total transmit power, subject to the constraint that each transmitter/ receiver attain a maximum allowed outage probability i.e., a minimum allowed quality of service and subject to limits on the individual transmitter power, we formulate the problem as follows:

minimize $P_1 + ... + P_n$

Subject to $P_i^{\min} \le P_i \le P_i^{\max}$, $i = 1, \ldots, n$ (3.3)

Here, $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum transmitter power for the transmitter *i*. To handle the resource allocation problem in cellular systems we introduce the cognitive radio scheme. For the channel allocation problem, the main goal is to bring more distribution of control. In cognitive radio scheme, each cell (base station) is managed by an agent. The resource in the system will be distributed and allocated through interaction between agents and limited to the domain of the agents. In other words, the channel allocation problem can be restricted to one domain, so that the agents can be placed in the base stations.

4. A new solution: Channel allocation based on CR

Introduction

In this section, we introduce a new channel allocation scheme based on cognitive radio scheme (CR) [9, 133]. Cognitive radio is a new and novel way of thinking about wireless communications. Using the cognitive radio in cellular systems will lead to a revolution in wireless communication with significant impacts on technology as well as regulation of spectrum usage to overcome existing lacks. The cognitive radio is a self-aware communication system that efficiently uses spectrum in an intelligent way [3]. Spectrum sensing defined as the task of finding spectrum holes by sensing the radio spectrum in the local neighborhood of the cognitive radio receiver in an unsupervised manner. The term "spectrum holes" stands for those sub-bands of the radio spectrum that are underutilized at a particular instance of time and specific geographic location. The task of spectrum sensing involves the following subtasks, detection of spectrum holes, spectral resolution of each spectrum holes, estimate of the spatial directions of incoming interference, and signal classification. After sensing, is to find a good transmission strategy that is aware of its surrounding environment to adapt their transmission parameters to the environment and the interference situation. It autonomously coordinates the usage of spectrum in identifying unused radio spectrum based on observing spectrum usage. Cognitive radios provide besides cognition in radio resource management also cognition in services and applications. A cellular network consists of an array of cells as illustrated in Figure 5. Each cell is managed by an agent. The cellular network is divided into clusters. For each cluster that consists of a number of cells (e.g. three), we set a control system which is called "distributor" (or cognitive distributor CD) [R2R5] to manage the cluster. The distributor informs the cells about the state of the resource in the cluster and manages the communication between the agents in the cluster. By using a distributor, we aim to reduce message complexity and channel acquisition delay. When a mobile host in a cell needs to communicate with another mobile host, it sends a request to the distributor to acquire a channel. The distributor then finds a free channel and informs the mobile host which channel it can use. The mobile host then starts using that channel. After the mobile host has finished using a channel, it informs the distributor that it no longer needs that channel. In addition, when a mobile host moves out of the cell while it is using a channel, the *handoff procedure* between of the old cell and its new cell ensures that the channels which the mobile host has been using in the old cell are relinquished and new channels are acquired to continue the ongoing communications in the new cell. The distributor can assign a free channel to another mobile host or relinquish (free) the channel so that it can be used by another cell. In this chapter (section 4.1-4.7) we describe the cognitive radio architecture based on agents, agent behavior, agent infrastructure, agent's communication strategy and agent reasoning strategy. In performance analysis, we discuss the cognitive radio scheme ability to improve the channel allocation in cellular systems. Furthermore, we perform a comparison between the cognitive radio and distributed dynamic channel allocations scheme. In this comparison we consider the interference and delay [R4]. Our studies show that under heavy load traffic, the number of interferes will be increased. A full rejection of the interference increases the blocking probability, which we aim to reduce. Based on QoS requirements [R1], some services can be allocated channel with the lowest interference. This can be achieved by increasing the frequency reuse within the minimum reuse distance. In second application, the cognitive radio scheme handles the power control. In the last section we have used the cognitive radio scheme in handoff process. Compared to distributed dynamic scheme, the cognitive radio scheme achieved to manage the handoff process so that to avoid the repeated unnecessary handoff in the own cell.

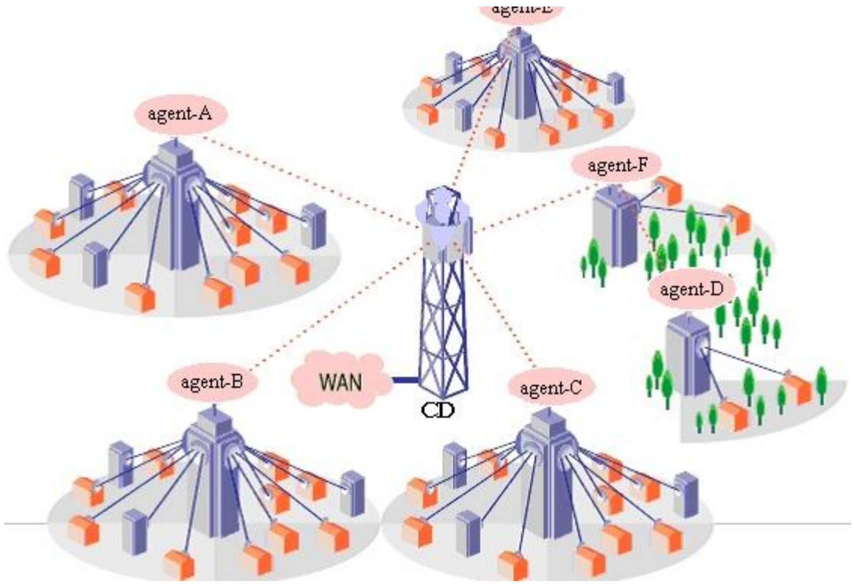


Figure 5: Basic idea

4.1 Channel model

We organized the cells in clusters, which consist of a number of cells, which we choose to be three, without loss of generality. Each distributor is in charge of one cluster. The basic idea behind the proposed channel allocation scheme is that if the set of n channels is divided into k disjoint *channel classes*, then potentially k cells (whose interference region overlap) can simultaneously acquire channels provided that they select channels from different channel classes. Let the Spectrum be partitioned into k subsets: $C_1, C_2, ..., C_k$, such that $Spectrum = \bigcup_{i=1}^{k} C_i$ and $C_i \cap C_j = \phi, (1 \le i, j \le k) \wedge i \ne j$ .We refer to C_i as *channel class i*. Furthermore, we assume that $C_i = \{r \mid ((r-1) \bmod k) + 1 = i\}$ and each channel class is of size $m(= n/k)$. Furthermore, we distinguish between two kinds of channels: nominal channel (or is called prime channel), this kind of channels will be used only in the home cell. Secondary channels: the secondary channel can be used in home and in neighbor cells [R5].

4.2 Communication strategy

Messages are a data oriented communication mechanism [R3], which will be used to transfer data between

- Cell to cell by using Request/ Response messages.
- Cell to distributor by using Inform messages.
- Distributor-A to distributor-B by using Informs messages.

i. Message types

In Figure 6, we illustrate the message, which will be used in the model.

- Inform message: the Inform message includes the cell's name, a time stamp [77], and the number of the available secondary channels.
- Re-inform message: the Re-inform message includes the name of the cell that has the highest number of free secondary channels.
- Request message: the request message includes the sender name, a time stamp that indicates the time of generating the request message, the receiver's name and the number of the secondary channels.
- Response message: the response message includes the sender's name, the receiver's name, a time stamp, and the requested channel number.

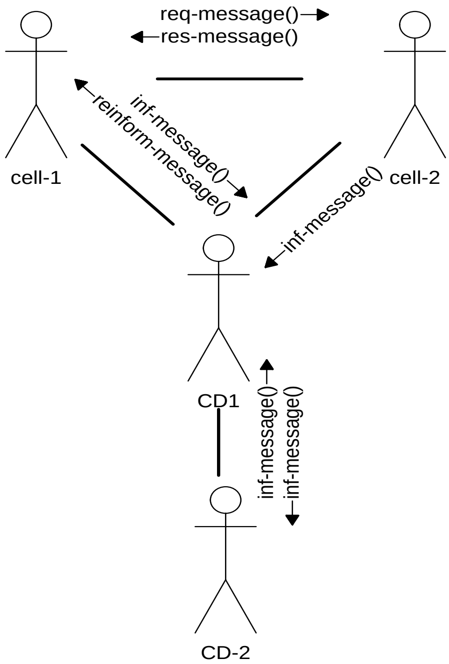


Figure 6: Message types

4.3 Distributor strategy

The distributor plays an important role in cognitive radio. It collects information about the state of the cells, updates its local information constantly, and concludes the proper decision, how and in which cell a channel should be allocated.

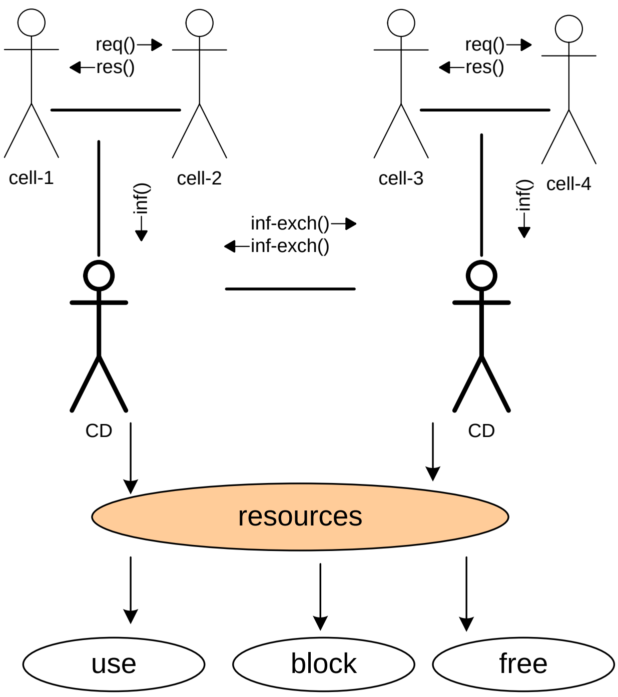


Figure 7: System architecture

A cell aims to increase spectrum efficiency followed by using a distributor to allocate free channels for new arriving calls in attempt to reduce call blocking probability. Channels will be assigned to new arriving calls according to *distributor task*, which will be described in three phases as follows:

- Autonomy: the distributor in cognitive radio should include a high degree of autonomy because of the desired features of complexity separation and fast response. When a new call in a cell arrives, the cell starts to search a channel. The call will be assigned a nominal channel, as long as there are still free channels. If all the nominal channels are busy, the cell starts the next phase to borrow a channel. A cell that needs a free channel sends Inform message to the distributor. The Inform message includes the sender's name, a time stamp, status, and receiver's name.
- Negotiation: cells often need to interact in order to improve their performance. One type of interaction that is gaining an increasing interest is *dynamic negotiation*. The goal of negotiation is the maximization of the utility of a future decision. In this phase, the agent in cell collects information about the channels states by using messaging exchange. After that, the cell sends request message to acquire a free channel. A free channel will be selected according to the number of free channels in the neighbor's cell.
- Reasoning**:** in this phase, cell updates its local information. When a cell acquires a free channel, it may be able to rely on complete information about channel states in its neighbor cells. And its main task is to select the right channel using *temporal reasoning strategy*.

We conclude from the above-mentioned features of the distributor that the distributor is simply an "intelligent software agent" [7-8, 24, 38, 63-64, 67-68, 73, 86, 109, 114, 130, 136, 140, 144]. In the next sections, we will use the both.

A. The cognitive radio algorithm

The innovation of the introduced cognitive radio existing by using the social agent that is SNR oriented. The algorithm is valid also for 2G, 3G and Next Generation. The algorithm involves new techniques like iterative swapping scheme that enables the algorithm to develop its rules to deal with new service challenges in the future. The social agent rules can be developed based on the updated its local information. Furthermore is the first cognitive radio algorithm that dealing with the repeated unnecessary handoff issue. In Figure 8, we show the main three phases that the cell passes through to acquire a channel from its neighbor cells.

i. When a new call arrives in a cell, the call will be allocated a free nominal (prime) channel.

ii. If all nominal channels in a cell are busy, the cell informs the distributor that it needs a free channel.

iii. The distributor updates its local information and informs the cell which channels are free. The distributor's decision is based on the number of the free nominal channels in cell. In this case, the distributor selects the cell with a highest number of free nominal channels.

iv. The cell requests the channel from its neighbor cell.

v. The neighbor cell response with grant if the channel is still free, or with reject if the channel is busy.

vi. If all channels are busy, then the distributor calculates the co-channel interference and the cell acquires the channel with a low interference that satisfied the quality of service requirements.

vii. In the case that there is no free channel in the cell, the distributor start the following phases to acquire a channel:

   a. Swapping process
   b. Handoff process

The two phases are described in detail in the next sections.

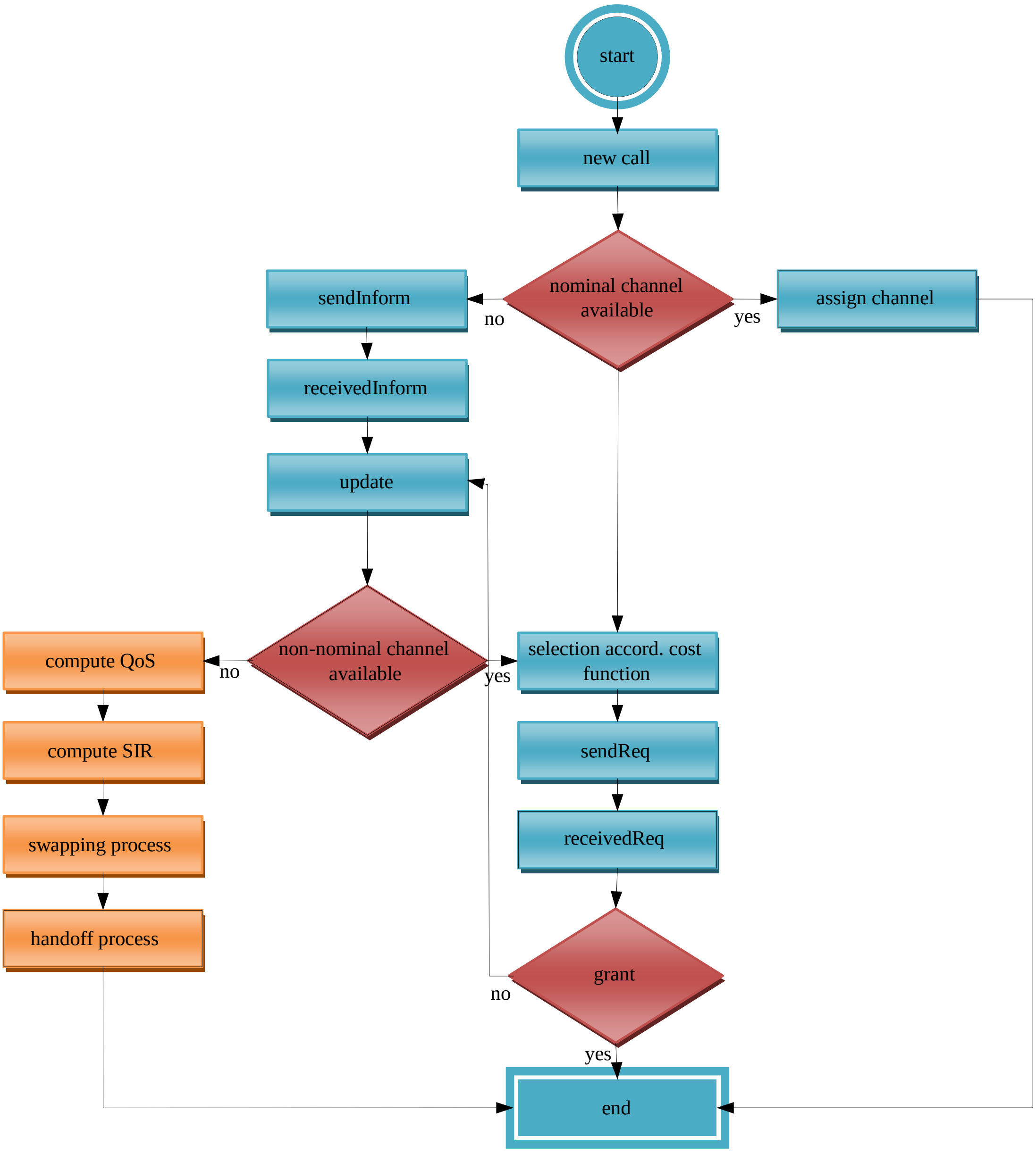


Figure 8: Cognitive radio algorithm

4.4 The structure of a cognitive radio scheme

The cognitive radio scheme consists of two main parts:

i. Activity Agent: the activity agent assigns the channels to new arriving calls based on the following features. Autonomy: Update its local information about the system states. Negotiation: message exchanging with neighbor distributors, and with resource agents. Reasoning: the activity draws the right conclusion with taking into consideration the varying load traffic, user's preferences and QoS-Parameters [R1].

ii. Resource Agent: Based on a cost function, the resource agent computes the co-channel interference.

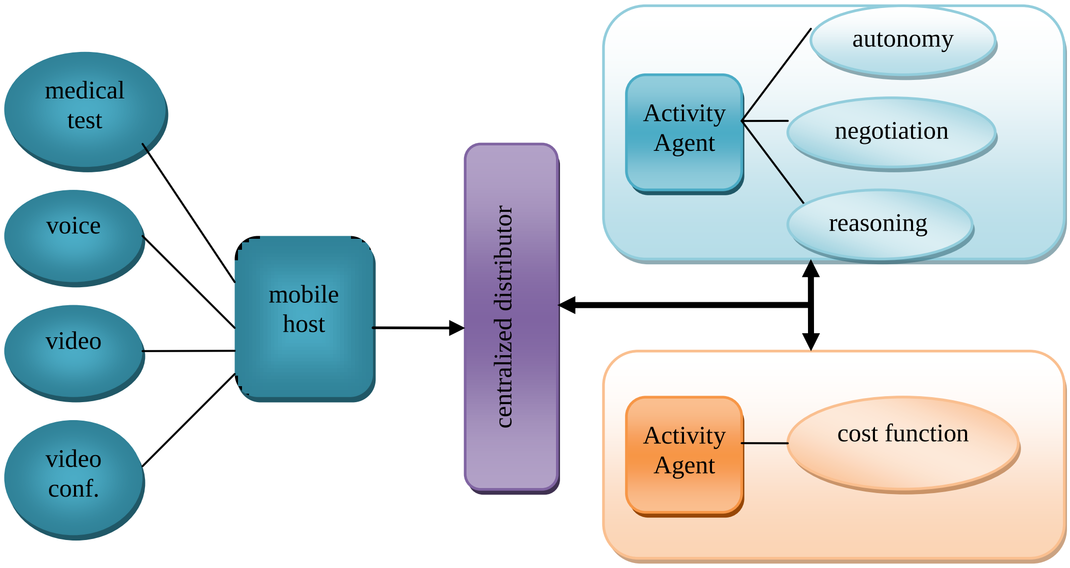


Figure 9: Cognitive radio infrastructure

4.5 Temporal reasoning strategy

The main idea of the channel allocation scheme is to evaluate the cost of each candidate channel and select the one that provides all interference constraints at minimum cost. When a new call is accepted into the network, it might cause quality deterioration of ongoing calls. The distributor draws its decision based on employing a cost function. The cost functions employed in [118] were slightly different to each other but the prime constraints remain the same basically. The Resource Agent allocates to a request the channel of which the cost function is minimal. The cost function basically computes the interference level. The cost functions can be collectively expressed in a general expression [R4]:

$$J_k = \sum_{i \in I_c} (C_{ki} q_{ki}) + q_c C_k \qquad (4.1)$$

For $\forall c, \forall k$, *where*, J_k is the channel interference cost unit for the *k*th channel, I_c denotes the set of co-channel interference cells related to cell *C*. C_{ki} denotes the binary status of I_c which signifies that

$$C_{ki} = \begin{cases} 0, \text{ if channel } k \text{ is available in cell } i \text{ without co-channel interference,} \\ 1 \text{ if channel } k \text{ is available in cell } i \text{ with co-channel interference.} \end{cases}$$

q_{ki} is used to reflect the interference between the interfering cell *i* and cell *C* and taken from the interference matrix (i.e., $q_{ki} = m_{ij}(t)$). C_k denotes the binary status of cell C which signifies that,

$$C_k = \begin{cases} 0, \text{ when there is no nomimal channels in the cell,} \\ 1, \text{ otherwise} \end{cases}$$

q_c is used to reflect the nominal channel occupied grade, the value of q_c is in proportion to that of q_{ki}, normally $q_c = 1$ if the nominal channel is being used in cell *C*. Therefore, any available channel having minimum value of J_k is to be allocated to a new call arising in cell *C*. In addition, in Figure 10 we describe the cost function introduced above. The distributor expresses the cell-i requirement (cell-i is the cell which needs a free channel to acquire). The neighbor cells inform the distributor about their state (e.g. which secondary channel is free, busy, or channel with co-channel interference). The distributor assigns the proper channel to cell-i. The proper channel is the channel with smallest co-channel interferences.

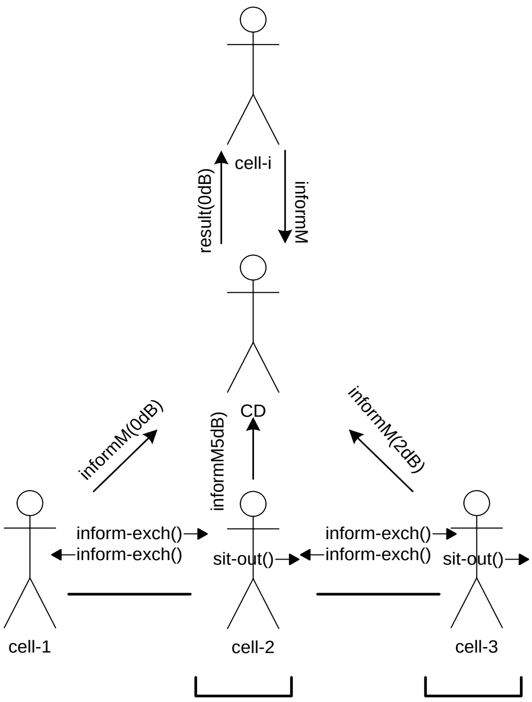


Figure 10: Cost function

The distributor can allocate channels based on different schemes. One of these for example, economically, a channel with interference can be allocated to a low QoS request, while a clear channel is allocated to a cell with high data rate. We conclude that the distributor works as a negotiator between $cell_i$, which searches for a free channel in its neighbor cells. In other words, the distributor offers the same task as the auctioneer in market based control. We note that distributors communicate between them by using message mechanism. The abilities of an algorithm quickly making decisions about the access channel and transmitted power are key issues of the quality of service. Before the cost function in equation (4.1) is combined with the power control algorithm to be used for network resource management in the next section, the performance of the cost function in channel allocation (without power control) must be evaluated. We need to know what is the benefit of the cost function based algorithm, compared with some traditional channel allocation algorithm and what is the time efficiency of the cost function based algorithm.

4.6 Behavior rules of agents

The new call in cell is blocked when there are no more free channels in the cell or the QoS requested cannot be provided as the SIR is under a given threshold SIR^{tgt}. In general by computing the call blocking probability in handoff process, we consider four social agent decision scenarios that are described below [R6].

i. Probability (Approve, $SNR > SNR^{tgt}$)
ii. Probability(Reject, $SNR < SNR^{tgt}$)
iii. Probability(Approve, $SNR < SNR^{tgt}$)
iv. Probability(Reject, $SNR > SNR^{tgt}$)

From social agent viewpoint, there are two kinds of decision, a good decision and a bad decision. A good decision, when the social agent can use a viable channel without to cause interference to the neighbor cells. A bad decision happened when the use of a viable channel may cause interference to other used channels. The mentioned four scenarios (social agent beliefs) can be expressed as follows: The resource assignment can be expressed and denoted by X, where $X \in \{1,0\}$. Which means, X = 1 or X = 0, denotes, respectively the channel is free or busy. The social agent decision can be expressed as following:

$$Y(decision) = \begin{cases} 1 & \text{acquire the channel X} \\ 0 & \text{otherwise} \end{cases}$$

- The Probability that the social agent accepts a free channel is given by $P(Y = 1 | X = 1)$
- The Probability that the social agent accepts a channel that may cause interference is given by $P(Y = 1 | X = 0)$.
- The Probability that the social agent rejects a free channel that may cause interference is given by $P(Y = 0 | X = 1)$.
- The Probability that the social agent rejects to acquire a busy channel is given by $P(Y = 0 | X = 0)$.

4.7 Iterative swapping prediction (ISP)

Currently, some global optimization tools in cellular networks are used. This kind of global optimization is resource consuming and expensive, for instance, Schema's optimization[1] requires a few hours to optimize a medium-sized cellular network. In other words, it is difficult for current cellular networks to react in real time to the users demands and optimize the networks. Furthermore the performance of these algorithms is very close to the optimal allocation algorithm. However, the complexity of these algorithms creates a large load for real-time application [113]. In cellular systems, some classes of traffic, such as voice, are much more sensitive to delays than other classes, such as data. To fulfill user's preferences and to improve the performance of the network, we introduce our approach based on social agent-oriented negotiation. The proposed negotiation scheme between the base stations enables each base station in the system to negotiate with its neighbor stations. The negotiation is based on messaging exchange between the social agents that manage the base stations. The goal of the negotiation is the maximization of the utility of a future decision. By identification of the resource of interference, the agent requests a transmit power reduction. For interference

---

[1] See www.schema.com

reduction, the agent uses the iterative distributed swapping scheme [R5] that can be summarized as fellow.

i. For *k* users the agent selects and allocates a set of free channels $r_i(t)$ from *V*.
ii. The social agent identifies the channels that cause interference.
iii. The channels will be ordered according to interference value.
iv. Comparing the interference of the assigned channels $r_i(t)$ to *v*.
v. The social agent selects a channel with the highest interference value and reduces the interference by swapping it as long as its interference is smaller than the accepted interference threshold ε. Furthermore the swapped channel kept the minimal reuse distance to avoid co-channel interference. In this ways the swapping scheme reduces the interference that caused between two or more resources at time *t* (min $d(r_i(t), v)$).
vi. Iteration ends when the specified time *t* is bigger than t_{max}.

t = 0
For i = 1 to k DO $r_i(t) = choose(V)$
REPEAT
For i = 1 to k DO $C_i = \phi$
FOREACH $v \in V$ *DO*
$x = \arg\min_{i:i\in\{1,\dots,k\}} d(r_i(t), v)$
ENDDO
For i = 1 to k DO
$r_i(t) = minimize(interf(C_i))$
UNTIL $(\forall r_i : d(r_i(t), r_i(t-1)) < \varepsilon,\ t > t_{max}$
RETURN $(\{r_1(t), \dots, r_k(t)\})$

The social agent that manages the resource allocation in the cell uses the iterative swapping scheme in the case that all channels are busy and the cell needs to acquire a more available channel, i.e. when the cell stands under heavy traffic load. We indentify the mutual interference channel (c.f.4.27). Hence we classify the channels into two groups. The first group includes the channels that cause interference. The second group includes the victim channels. The victim channels are channels that have been interfered by others channels. For each victim channel is calculated the interference level and assigned score respectively. We take a victim channel with highest interference score. Then we indentify which channels in the neighbor cells interferes that victim channel. After that the social agent starts to negotiate with the neighbor cells. The goal of the negotiation is to re-allocate the channel that causes mutual interference with other free available channel in the neighbor cell. The social agent attempts with all neighbor cells gradually. The iterative swapping process is scheduled, because we take into consideration the quality of service (QoS), especially the delay. We introduce a simple example referred to SNR (see section 4.9.A) to explain the basic idea of the iterative swapping scheme. It is assumed that the base station in cell *A* propagates a strong signal power as illustrates in Figure 11. The neighbor cell *B* receives this signal power and causes interference in cell *B.* The social agent in cell *B* manages negotiation with cell *A* in order to reduce the signal power so that covers the needed area without to cause any interference to other channels in neighbor cell. This issue is known as signal power balancing (regulation) that will be discussed in detail in section 4.8.8. Beside the iterative swapping scheme the social agent allocate the channel according to quality of services parameters. The last option, when the all channels are busy, the social agent forces the mobile station to handoff early in order to avoid call blocking.

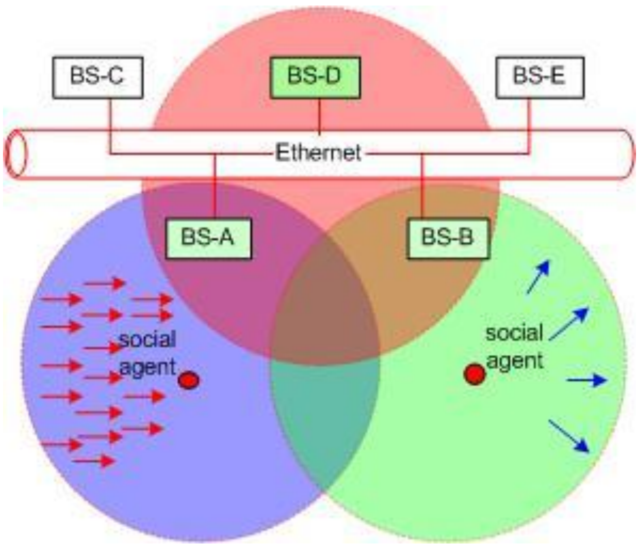


Figure 11: Antenna propagation

Figure 12 illustrates the received signal power in the cell (c.f.4.26). In the cellular system, the cell receives different signal power from the neighbor cells. This matter has been discussed in details in section 4.9.B.

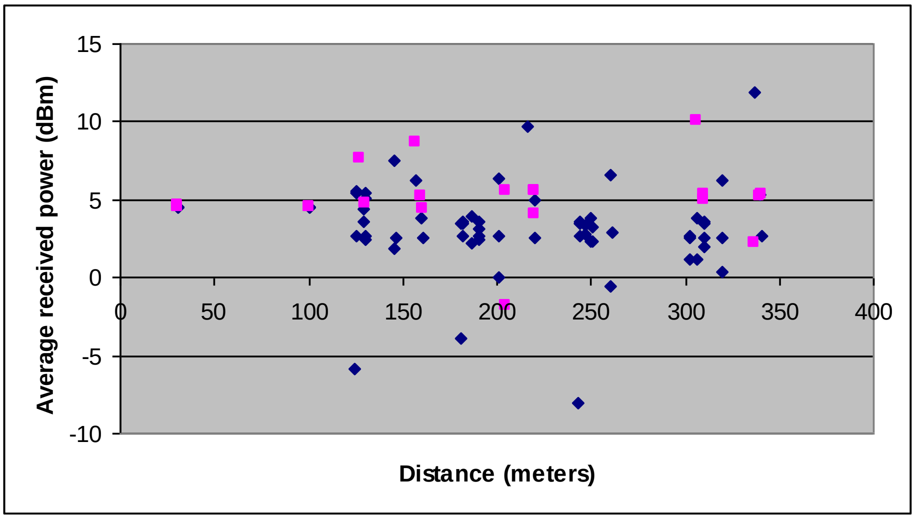


Figure 12: Average received power

Figure 13 illustrates the results of running the iterative swapping scheme that placed in the base station. Figure 13 shows the received power signal of two cells. Furthermore in the Figure 13 we see also that the signal power is regulated in each base station in order to reduce the mutual interference. Based on the power signal regulation each mobile station receives a power signal from its home cell.

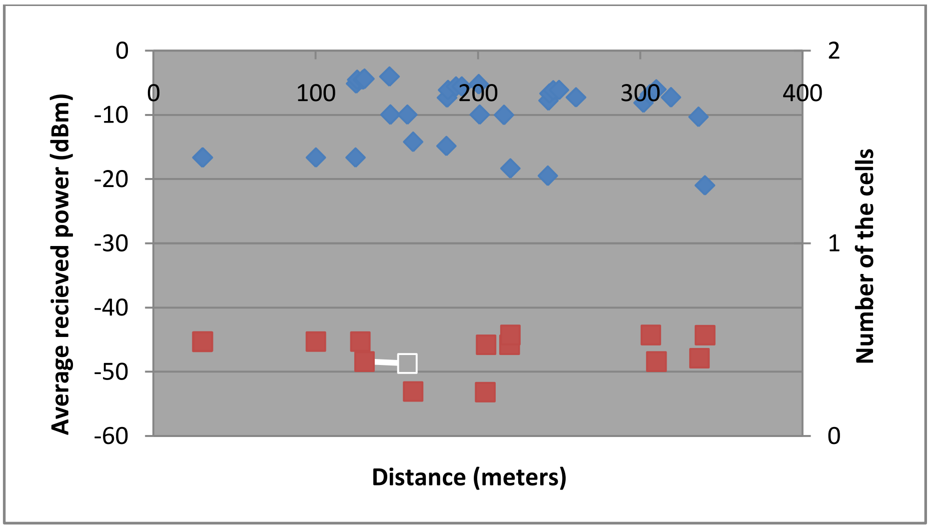


Figure 13: Channels distribution

4.8 Algorithm analysis

In this section, we introduce and discuss a simple model of our proposed channel allocation algorithm based on cognitive radio. We compute the delay in the system caused by messages exchange and resource acquisition time. The distributed dynamic channel scheme is based on basic search scheme [41].

4.8.1 The delay calculation

By multimedia communication, the QoS [R1] should be controlled, especially the delay, which will be handled in this section. Delay is the second main reason beside the interference, which increases the call blocking probability in cellular systems. The situation is made more complex by the fact that the quality of service varies over time on the same system, due to the need to share resources between a variable numbers of other users. It is important to be aware of the processes by which QoS can be determined, negotiated, and varied before or during the operation of an application. To get a high QoS, we have to discuss the quality of service requirements for multimedia communication systems, the use of source characterization in channel allocation, the characteristics of multimedia traffic, and QoS requirements for multimedia traffic. In next section we calculate two parameters which are caused by the delay in the system.

i. Message complexity in CR

As illustrated in Figure 7 we calculate the message exchange between the cells and between the cells and the distributor. The request messages are considered between the cells in order to acquire a secondary channel is described in figure 6. The inform messages are considered between the cell and the distributor *D* in order to update the local information in the social agent and in the distributor. The inform message is sent when a channel is acquired or released. In previous section we have mentioned that the channels are divided into prime channels and secondary channels. In this section we calculate the message exchanges that is need to acquire a prime channel and the number of the messages that are needed to acquire a secondary channels. Furthermore we take into consideration when the cell is under heavy load traffic. In this situation is considered that the cells may need more one attempt to acquire a secondary channel.

- The number of the request messages for acquisition prime channel is zero, because the prime channel is used only from its home cell.

- The number of distributor's inform messages.

  $2\times n\times n_c$ (4.3)

- The number of inform messages in the system

  $$D\times\sum_{c=1}^{m}2\times n\times n_c \quad (4.4)$$

- The number of message for acquisition a secondary channel

  $2\times n\times n_c + 2\times n_r\times n_c$ (4.5)

- The number of the message for acquisition a secondary channel in the system

  $$D\times\sum_{c=1}^{m}(2\times n\times n_c)+\sum_{c=3}^{m}(2\times n_r\times n_c) \quad (4.6)$$

- It takes several attempts in case of conflict and thus number of message will be increased

  $2\times n\times n_c + 2\times n_r\times n_c\times m$ (4.7)

- The number of message in the system by occurrence conflicts

  $$D\times\sum_{c=1}^{m}(2\times n\times n_c)+\sum_{c=1}^{m}(2\times n_r\times n_c\times m) \quad (4.8)$$

- We assume that λ is the ratio of the acquired prime channels to the total number of channels, where $1 \geq\lambda\geq 0$, hence $(1-\lambda)$ is the ratio of secondary channels.
- Average number of messages for channel needed

  $\lambda\times 2\times n\times n_c+(1-\lambda)(2\times n_r\times n_c\times m)$ (4.9)

  where

  - n is the sum of acquisition and release messages.
  - n_c the number of cells
  - n_r the sum of request and response message
  - m is the number of the cell's attempts to acquire a channel.

ii. Message complexity in DDCA

In this section we consider the distributed dynamic channel allocation strategy based on search-update scheme. In the search-update scheme, the inform messages, the request messages and the response messages are exchanged between the cells in order to acquire a free available channel. We note that in distributed dynamic channel allocation there is no distributor as by cognitive radio. The cell firstly send the inform message to all neighbor cells in order to update its local information about the state of the channels in the neighbor cells.

Hence it sends a request message to acquire a free available channel. It is necessary to know that the cell will set the received message in the queue if it is in the search phase. We take into consideration the case in which the cell is under heavy load traffic may occur conflict. Then the cell needs a lot of attempts to request a channel. Due the delay may include the message false information so that two cells acquire the same resource.

- The number of cell's inform messages

  $2 \times n \times n_c$ (4.10)

- The number of message for acquiring a channel

  $2 \times n \times n_c + 2 \times n_r \times n_c$ (4.11)

- If a conflict occurs, it takes several attempts to acquire a channel and the number of message will be increased

  $2 \times n \times n_c + 2 \times n_r \times n_c \times m$ (4.12)

where

- n is the sum of acquisition and release messages.
- n_c the number of cells
- n_r the sum of request and response message
- m is the number of the cell's attempts to acquire a channel.

In the Figure 14 we illustrate a cluster size of seven cells. The number of cells increases over the simulation duration from seven cells till forty two cells. Furthermore we show the number of the sent messages from one cell that needed to acquire a secondary channel.

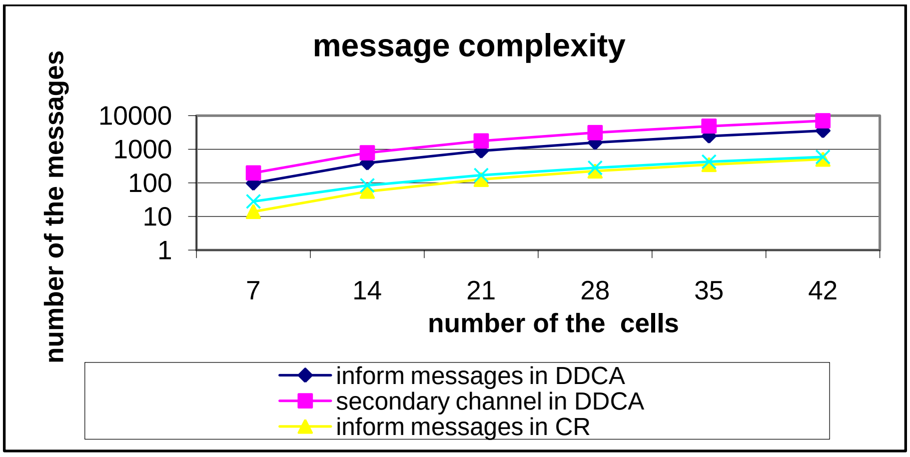


Figure 14: Message complexity CR vs. DDCA

iii. Channel acquisition delay in CR

The message complexity plays an important role in the channel acquisition delay. We note that the term channel acquisition delay and the term channel acquisition time have the same meaning. In this section we calculate the time that a cell needed to acquire a secondary channel.

- The expected or average channel acquisition time for prime channel is zero.
- The expected or average channel acquisition time for secondary channel without conflicts is given by

  $T_{res.acq.time} = T_{CD} + T_{CC}$ (4.13)
- The expected or average channel acquisition time for a secondary channel in the system without conflicts

  $$D \times \sum_{c=1}^{m} (T_{CD} + T_{CC}) N_c \quad (4.14)$$

  where $T_{CD} = 3 \times T_{inform}$ and $T_{CC} = 2 \times T_{rr}$.
- Average acquisition delay for secondary channels with conflicts

  $T_{res.acq.time} = T_{CD} + T_{CC} \times m$ (4.15)
- Average acquisition delay for secondary channel in the system with conflicts

  $$D \times \sum_{c=1}^{m} (T_{CD} + T_{CC}) N_c \times m \quad (4.16)$$
- $T_{neighbour}$ is the average acquisition time between two Distributors.

  $T_{neighbour} = 2 \times T_{DD}$ (4.17)

  where

- T_{CD} is the average time needed for message exchange between cell and Distributor.
- T_{CC} the time needed for message exchange between two cells.
- T_{rr} the time needed for request/response messages.
- N_c is the number of the cells.

iv. Resource acquisition time in DDCA

- The expected or average channel acquisition time for a channel without conflicts is given by

  $T_{res.acq.time} = 2 \times T_{inform} + 2 \times T_{rr}$ (4.18)
- Average acquisition delay for a channel with conflicts

$$T_{res.acq.time} = T_{attempt} \times N_{attempt} \times N_{deferred} \quad (4.19)$$

where

- $T_{attempt}$ is the average time spent on each attempt.
- $N_{attempt}$ is the average number of attempts needed to acquire a channel.
- $N_{deferred}$ is the number of requests deferred by a central controller in its DeferQ.

When a conflict occurs, the requesting cell has to wait an extra time *W*. To compute $N_{deferred}$ we need to consider the arrival process and service process at the queue DeferQ.

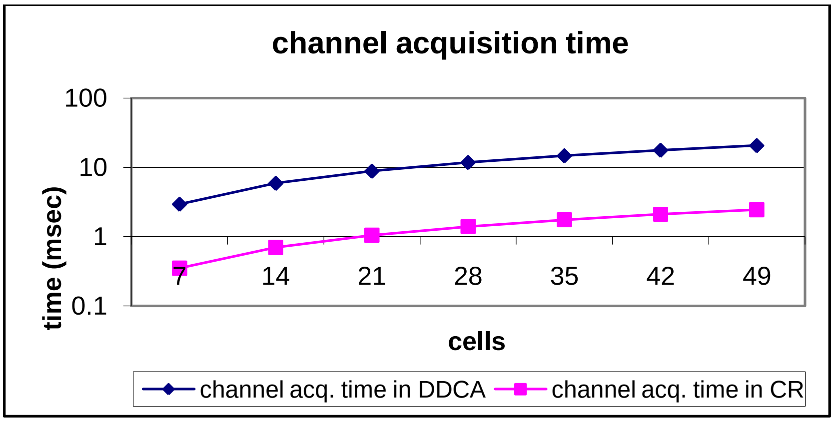


Figure 15: Channel acquisition time

In the distributed dynamic channel allocation, when a new call arrives in a cell, the cell sends request messages to its neighbor cells. The channel can be used, when the cell receives a response message from its neighbor cells. Figure 15 illustrates the time that is needed to acquire a secondary channel without occurring a conflict in the cluster. The cluster size consists of seven cells. Furthermore the Figure 15 shows that when the cluster size becomes bigger then it is needed more time in order to acquire a channel, because the number of the messages that will be exchanged between the cells will be increased too. We conclude that increasing the cluster size will increase the time that needed to acquire a channel.

4.8.2 The interference calculation

Interference is the major limiting factor in the performance of wireless communication systems. It has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls. Frequency reuse implies that in a given coverage area there are several cell that use the same set of frequencies. These cells are called co-channel cells, and the interference from users with the same channel in the other co-channel cells is called co-channel interference. Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by simply increasing the carrier power of a transmitter. This is because an increasing in carrier transmit power will increase the interference to neighboring co-channel cells. To reduce co-channel interference, co-channel cells must be physically separated sufficiently by a distance, called as reuse distance. For a network with the limited amount of frequency channels, a large reuse distance (cluster size) can guarantee a high quality of service to the system, but the capacity will be decreased due to the decrease of the channel number in a cell. Another interference of cellular systems is the adjacent channel interference. Adjacent channel interference results from imperfect receivers filters which allow nearby frequencies to interfere the using frequency channel. Adjacent channel interference can be minimized through careful filtering and channel assignment. Since each cell is given only a fraction of the available channels, a cell need not be assigned channels, which are all adjacent in frequency. By keeping the frequency separation between each channel in a given cell as large as possible, the adjacent channel interference may be reduced considerably. However, if the frequency reuse factor is small, the separation between adjacent channels may not be sufficient to keep the adjacent channel interference level within tolerable limits. In cellular radio system, sources of interference include mobile units in the same cell, a call in progress in a neighbor cell, other base stations operating in the same frequency band. Interference on voice channels causes cross talk, as the subscriber hears interference in the background due to an undesired transmission. On the control channels, interference leads to missed and blocked calls due to errors in the digital signaling. The types of system-generated cellular interferences to high-performance digital wireless communication systems are co-channel interference and inter-symbol interference, which is caused by the frequency selectivity (time dispersion) of the channel due to multi-path propagation. One of the physical measures of RF channel quality is the *carrier-to-interference* or *C/I ratio*. This ratio is logarithmically proportional to the signal quality enjoyed by the receiver of the signal. The larger the C/I ratio, the better is the channel quality. C/I ratios of 17 dB are ideally used to determine the edge of coverage for a cell. If the measured C/I fall below this level, the mobile should be in the coverage region of another cell and a cell handoff should be performed. The interior of the cell should provide C/I ratios, which exceed 17 dB, unless the mobile is located in an RF coverage "hole." In next section, we compare the co-channel interference between the three main channel allocation strategies, FCA, DCA, and CR.

4.8.3 Identification of the interference source area

For simplicity, we assume in this section that each base station to have the same transmitted power *P* on each channel with an omnidirectional antenna. Fast fading is not considered. The propagation model is assumed to have an average path loss exponent η. Then the received power of desired signal for mobile *p* in cell *i* and that of the interference signal from the link of mobile *q* in the *k*-th cell, respectively [17], are

$$S_{ip} = A.P.r_{ip}^{-\eta}.10^{\frac{\xi_{0ip}}{10}} \tag{4.20}$$

$$I_{kq} = A.P.d_{kp}^{-\eta}.10^{\frac{\xi_{kp}}{10}}\beta_{pq} \tag{4.21}$$

Where *A* is a proportional constant; r_{ip} is the distance between mobile *p* and the base station of the serving cell *i*, d_{kp} is the distance between mobile *p* (in cell *i*) and the base station of the *k-th* interfering cell; η is the an average path loss exponent; ξ_{0ip} and ξ_{kp} are lognormal random variables (in *dB*) which refer to the slow fading of the desired signal of mobile *p* and the interference signal from the base station of interfering cell *k* respectively; β_{pq} is the attenuation factor (with respect to channel *q* to channel *p*) of interference by receiver filter. The attenuation factor, β_{pq}, is introduced to describe the co-channel interference and the adjacent channel interference with one formula. For the co-channel interference, β_{pq} becomes 1, but for the adjacent channel interference, β_{pq} depends on the receiver filter characteristic and the channel separation between channel *p* and channel *q*. The desired signal and interfering signals, and different individual interfering signals are all assumed to be statistically mutually independent. From Equation (4.20) and (4.21) the signal to interference ratio (SIR) is obtained

$$SIR = \frac{S_{ip}}{\sum_{k\in\{n_i\}}\sum_{q\in\{m_k\}} I_{kq}} \frac{1}{\sum_{k\in\{n_i\}}\sum_{q\in\{m_k\}} w_{kq}} \tag{4.22}$$

where $\{n_i\}$ denoted the interfering cell set for host cell *i*; $\{m_k\}$ is the assigned channel set in the *k-th* interfering cell. Let

$$w_{kq} = \left(\frac{d_{kp}}{r_{ip}} \right)^{-\eta} 10^{\frac{\xi_{kp} - \xi_{0ip}}{10} \beta_{pq}} \tag{4.23}$$

The term w_{kq} is the contribution to the SIR reciprocal of call p in cell i by the admission of call q in cell k. The effect on the SIR value of the existing call p due to allocating channel q in cell k can be calculated from the term of w_{kq}. However, the signal to interference ratio (SIR) [17, 56] for the *k-th* channel in the cell i can thus be generally written as

$$SIR_i = \gamma_i = \frac{G_{ii} P_{ik}}{\sum_{j=1}^{M} G_{ij} P_{jk} + N_i} \tag{4.24}$$

Where P_{ik} denotes *k-th* channel down link effective radiation transmission power from the base station of the cell i and G_{ij} be the radio propagation gained on the path from the base station of cell j to the mobile user in cell i. suppose that the same channel is used in cell i and reused in cell j with the transmission power P_{jk}, the product $G_{ij}P_{jk}$ becomes the amount of the co-channel interference to the active user in cell i from cell j. M is the number of co-channel users in the system and N_i is the additive White Gaussian Noise of the cell i. In this case, the agent selects the channel, which is affected at least from the source interference of the neighbor cell.

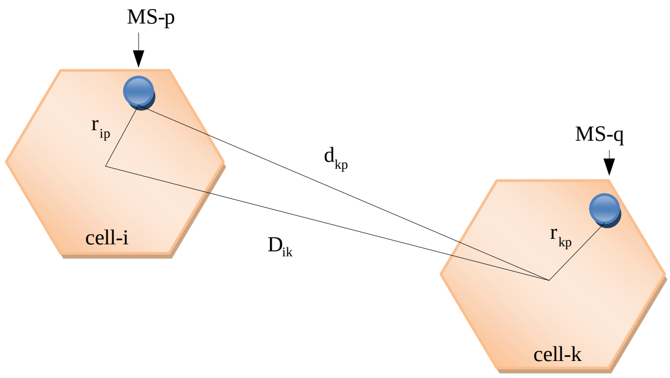


Figure 16: Co-channel interference

4.8.4 Identification of the interference victim area

In this section, we focus on a simple two-user model to gain insights of the impact of the radio channel characteristics, heterogeneous traffic intensity. Two users (denoted as users 1 and 2) are located at a distance of d_1 and d_2 to from the serving base station, respectively. Without loss of generality, we assume that user 1 is closer to the base station than user 2, i.e., $d_2 \geq d_1$. Denote P_t as the transmitter power of the base station, G the antenna gain, d the distance between the transmitter and receiver and N_0 as the thermal noise power. Generally, then, the received signal-to-noise ratio (SNR) [56, 58] at the *k-th* user in cell-1 is given by

$$\gamma^{1}_{1(d_1)} = \frac{P_t G(d_1)}{N_0}, \gamma^{1}_{2(d_2)} = \frac{P_t G(d_2)}{N_0}, \ldots, \gamma^{1}_{j(d_k)} = \frac{P_t G(d_k)}{N_0} \tag{4.25}$$

for $j = 1, \ldots, k$. The signal-to-noise ratio (SNR), γ_k defined as the ratio of a signal power to the noise power corrupting the signal. The average blocking probability of user *k* being served by the base station based on calculation of the interference area for cell *i*, which is greater than a given target value for cell *i*, γ_i^{tgt}. This blocking probability [R5] is:

$$P_b = \frac{1}{n}\sum_{k=1}^{n}\delta_k \ , \quad \text{where} \quad \delta_k = \begin{cases} 1 & \left(\gamma_k - \gamma_i^{tgt}\right) < 0 \\ 0 & Otherwise \end{cases}. \tag{4.26}$$

4.8.5 Co-channel and adjacent channel reuse ratio probabilities in FCA

In FCA algorithm, there is exactly once case, because according to FCA design strategy, the channels are a priori fixed allocated to cells with taking into consideration, maintaining the minimum reuse distance $D_{min.}$ Otherwise, the call will be blocked [R3].

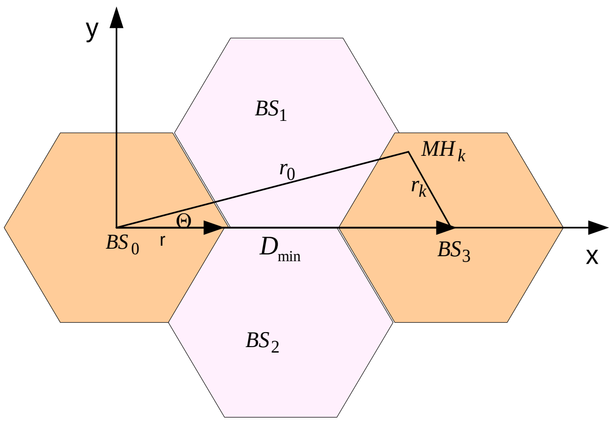


Figure 17: Co-channel in the FCA

4.8.6 Co-channel and adjacent channel reuse ratio probabilities in DCA

We assume that the mobile host M_0 exists in the reference cell (radius *r*) at some radius *ρ* from the reference site F_0 as illustrated in Figure 18. The interfering mobile host M_i is assumed to be within the service area of radius D_{min} and is at some radius *Π* from F_0. The signal received at F_0 from M_0 is denoted as *s*, the interference received at F_0 from M_i as *i*, and the signal to interference ratio *s/i* as *z*. The channel reuse ratio is given by $D_{min} = \Pi/r$. Based on distance propositional to radius, we distinguish two cases:

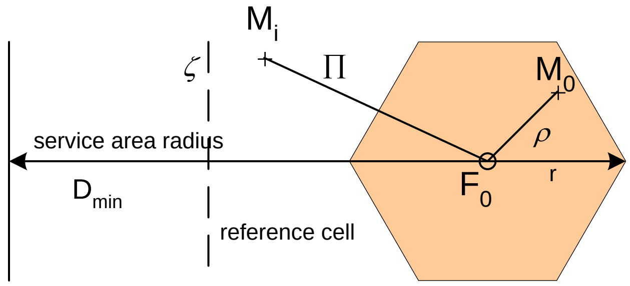


Figure 18: Co-channel in the DCA

First case, the distance Π is smaller than the radius r. $\Pi < r$.

In this case, the interferer M_i generates sufficient interference, which leads to miss and to block calls.

Second case, the distance Π is bigger than D_{min}. $\Pi > D_{min}$

In this case, the interferer M_i cannot generate sufficient interference at F_0 to cause M_0's link to fail, regardless of location. When $\Pi > D_{min}$, the signal to interference ratio *z* will always be greater than or equal to *Z*. In DCA strategy, a channel can be selected from the pool, and allocated to cell, if the channel does not interfere with another channel.

4.8.7 Co-channel and adjacent channel reuse ratio probabilities in CR

We consider Figure 18, in which we assume that the mobile host M_0 exists in the reference cell (radius *r*) at some radius ρ from the reference site F_0. The interfering mobile host M_i is assumed to be within the service area of radius D_{min} and is at some radius Π from F_0. The signal received at F_0 from M_0 is denoted as s, the interference received at F_0 from M_i as *i*, and the signal to interference ratio s/i as *z*. The channel reuse ratio is given by $D_{min} = \Pi/r$. Based on distance propositional to radius, we distinguish three cases [R3]:

First case, the distance Π is smaller than the radius *r*. $\Pi < r$.

In this case, the interferer M_i generates sufficient interference which leads to miss and to block calls.

Second case, the distance Π is bigger than D_{min}. $\Pi > D_{min}$

In this case, the interferer M_i cannot generate sufficient interference at F_0 to cause M_0's link to fail, regardless of location. When $\Pi > D_{\min}$, the signal to interference ratio z will always be greater than or equal to Z.

Third case, the distance Π is between r and $D_{\min}$. $D_{\min} > \Pi > r$

To compute the value of ζ, we are assuming a single-slope distance-dependent path loss propagation model. With this model $s = \kappa P_t \rho^{-\gamma}$ and $i = \alpha\kappa P_t \Pi^{-\gamma}$, where α is the relative strength of the interferer (for a co-channel interferer α =1). K is an RF constant, P_t is the transmit power and γ is the path loss exponent. The minimum possible signal power occurs when M_0 is at the periphery of its cell, i.e. $s = \kappa P_t r^{-\gamma}$, hence the minimum signal to interference ratio for M_0 is given by:

$$z = s/i = \frac{\kappa P_t r^{-\gamma}}{\alpha\kappa P_t \Pi^{-\gamma}} = \frac{1}{\alpha}\left(\frac{\Pi}{r}\right)^{\gamma} = \frac{1}{\alpha}\left(\frac{rD_{\min}}{r}\right)^{\gamma} = \left(\frac{D_{\min}}{\alpha}\right)^{\gamma} \tag{4.27}$$

When $z = Z, \zeta = rD_{\min} = r(\alpha Z)^{1/\gamma}$

$$z = \frac{i(\Pi, r)}{s} = \alpha\left(\frac{r}{\Pi}\right)^{1/\gamma} \tag{4.28}$$

As we have already mentioned, the capacity is directly affected by the interference, less interference yield a higher systems capacity. The interference consists of two kinds:

i. The first kind, interference which is occurring within the cell itself, i.e. $I_{in} = (N_s - 1)S$

ii. The second kind, which is coming from neighboring cells. $I_{neighbor} = \frac{I(r_k, r_0)}{S} = \alpha\left(\frac{r_k}{r_0}\right)^{1/\gamma}$.

We note that we have ignored the effect of the first kind of the interference in this research. Hence, based on the above described interference, the path loss [45] is usually characterized by

$$PL(r) = 10\alpha \log_{10}\left(\frac{r}{r_0}\right) + L_0 \tag{4.29}$$

Where r is the distance between a transmitter and a receiver, α is the path loss exponent, and L_0 is the nominal path loss at the known reference distance r_0. By using path loss models to estimate the received signal level as a function of distance, it becomes possible to predict the SNR for a mobile communication system. Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor radio channels. We analyze the performance of market-based model based on call blocking probability and compare it to the DCA. We assume 7×7 hexagonal cells. The total number of channels in the system is 70. In market-based model, we consider the cell, which requests a channel as consumer, and the cell which lends a channel as producer. The consumer and producer try to maximize their utility respectively. The maximization of the consumer utility leads to the consumers demand:

$$r_{Di}(k) = R*(1/(C/I)) \qquad (4.30)$$

The consumer's demand depended on the Resource R and the co-channel interference (see section 4.8.2). Figure 19 illustrates the user positions (distance) related to the C/I**.** Furthermore Figure 19 shows that the position of the user in the cell plays an important role. The channel can be acquired when the minimal distance is kept in order to avoid the co-channel interference. If the minimal distance is reduced, the co-channel interference will increase. The co-channel interference issue has been handled and discussed in details. (see section 4.8.5/.6/.7)[R3].

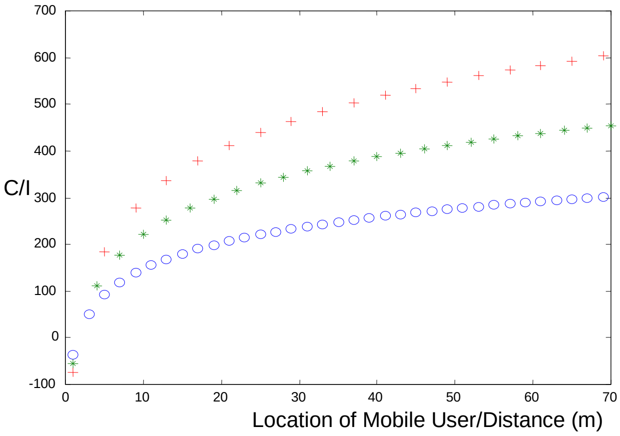


Figure 19: Co-channel interference

To calculate the call blocking probability we have used the Elang Formula [2]. Traffic intensity can be measured using two dimensionless units: Erlang and circuit centum seconds (CCS). The Erlang is a unit named in memory of Anders K. Erlang, the founder of traffic theory. One Erlang is equivalent to one circuit (or trunk) in continuous use, and it can be translated as the number of calls (made in one hour) multiplied by the duration of these calls (in hours). Each call has a different duration or a different *call holding time*; for traffic intensity measurements the *average call holding time* is taken into account. This has different values for business or private subscribers, but the typical values for average call holding time vary between 120 and 180 seconds. Therefore, the traffic intensity in Erlangs can be defined as: $\mathrm{T(in\ Erlangs)} = \mathrm{(number\ of\ calls\ in\ an\ hour)} * \mathrm{(average\ call\ holding\ time(s))/3600}$

Traffic intensity can also be measured in CCSs. One CCS is equivalent to one circuit in continuous use for 100 seconds. The traffic intensity measured in CSS is:

$$\mathrm{T(in\ CCSs)} = (\text{number of calls in100s}) * (\text{average call holding time(s)})/100$$

In 1917, Erlang developed an equation, which expresses the probability of a call being blocked (P_b), as a function of the offered traffic (T), and a number of circuits (or trunks) (C).

$$P_b = \frac{T^C}{C!} \Bigg/ \left(1 + \frac{T}{1!} + \frac{T^2}{2!} + \ldots + \frac{T^C}{C!}\right) \qquad (4.31)$$

Using equation (4.31), it is possible to determine the number of channels required to support a certain offered traffic given the desirable GOS. Equation (4.31) is called the Erlang B formula. Figure 20 illustrates a comparison in new call blocking probability between cognitive radio and dynamic channel allocation. The call blocking probability in cognitive radio is lower than in dynamic channel allocation, because in cognitive radio, some services may be allocated channels with low interference. However, it is not possible in dynamic channel allocation. We distinguish between three levels of interference as mentioned in the previous section. The first level contains the channel with high interference values. In this case, the channel is blocked. The second level is contains the channel with low interference. In this case, the channel can be used temporary. And the third level contains channel without interference in the case that the minimal distance between cells is kept.

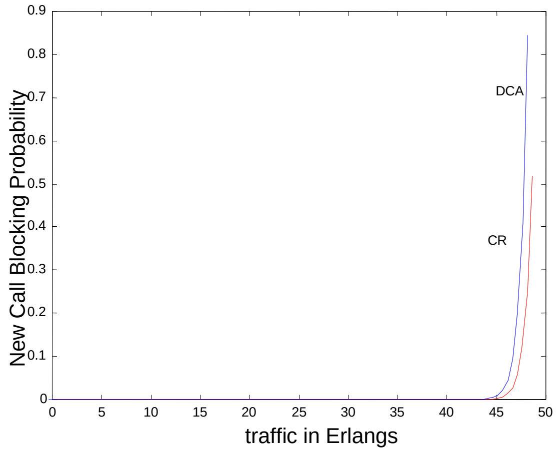


Figure 20: Call blocking probabilities

Figure 21 describes the free space propagation model, the propagation condition is assumed idle and there is only one clear line-of-sight path between the transmitter and the receiver (see section 1.4.B). Figure 22 shows the path loss exponent in urban environment (eq. 1.15). The propagation model related to the SNR it has been discussed in details in sections 4.9 A and 4.9.B. When the mobile user is closed to the antenna, it receives a good signal and the path loss is smaller.

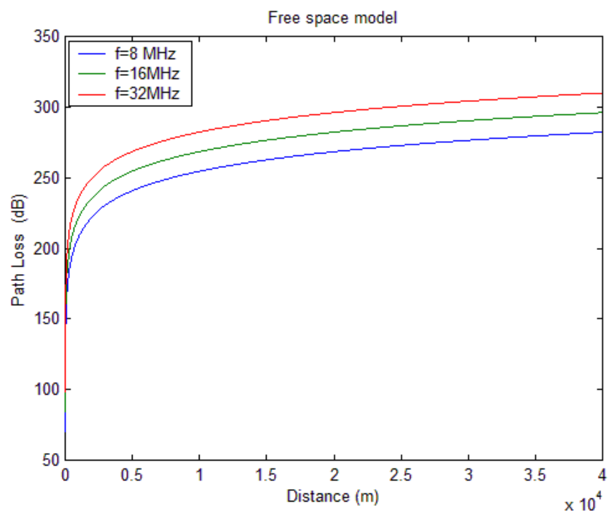


Figure 21: Path loss with logarithmic scale

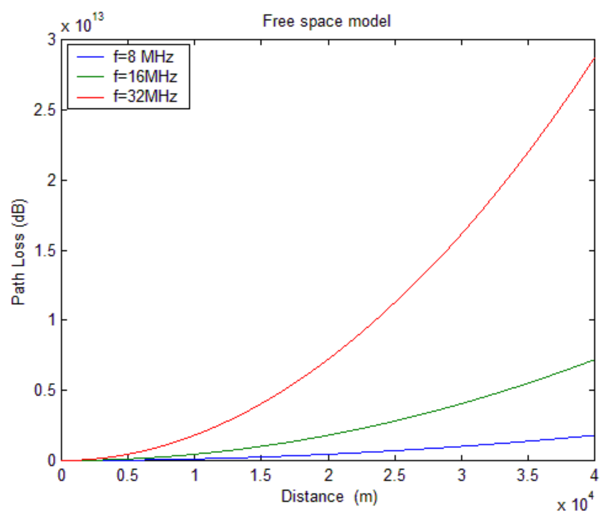


Figure 22: Path loss vs. distance

4.8.8 Radio spectrum management

There is a lot of research and investigation by many industrial organizations on the closely related topics of dynamic spectrum management. In this section, we introduce spectrum management based on cognitive radio, in which the spectrum sharing and flexible spectrum access. Spectrum sharing based radio cognitive plays thereby an important role to increase spectrum utilization, especially in the context of open spectrum. Cognitive radios [3, 67, 104] use flexible spectrum access techniques for identifying under-utilized spectrum and to avoid harmful interference to other radios using the same spectrum.

- **Power control based on CR**

The control problem is the regulation of the resource distribution in two cells as shown in Figure 23.

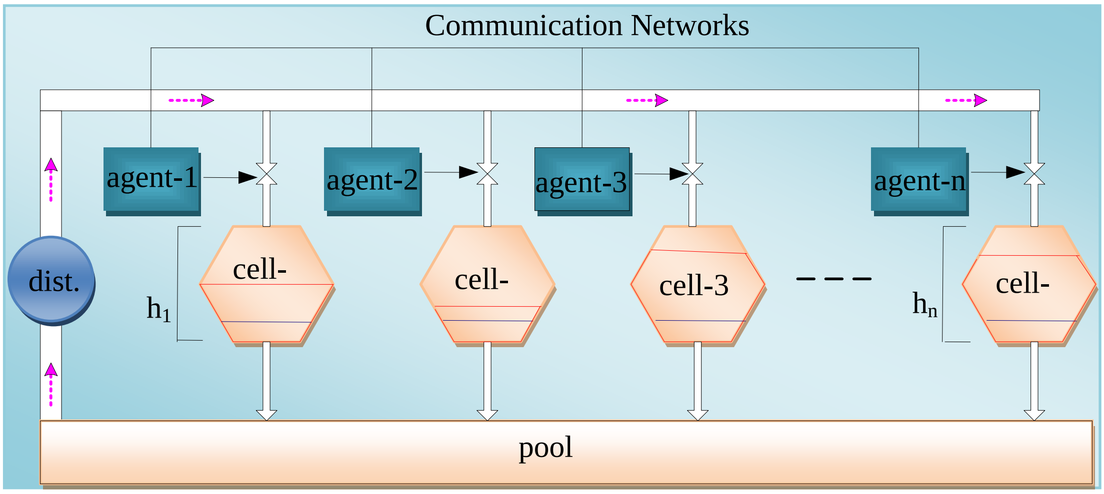


Figure 23: Resource control

Each cell *i* can acquire amount *i* while the level in the cell is denoted by h_i (the demand of channel in each cell depends on the arrival call in the cell). We assume, that the mass flow of resource in the cell *i* is proportional to the value position u_i (call arrival rate). And we consider that the resources in the system are limited. The vector of the required setpoints of the levels, (to meet the call arrival rate), are given by h_s. We further assume that the equilibrium point (u_0, h_s) is known (channel allocation). The control task is the regulation of disturbances (plus the interference) of the resources in the cells. Each cell is considered as a single subsystem and associated with an agent. The input variable of each agent *i* is the deviation $\Delta h_i(k)$ of the resource amount.

$$\Delta h_i(k) = h_i - h_s \tag{4.31}$$

The output variable is the value position

$$u_i(k) = \Delta u_i(k) + u_0 \tag{4.32}$$

Which is the sum of the deviation $\Delta u_i(k)$ and the equilibrium position u_0. Since the equilibrium position is known, the agent only has to compute the output variable $\Delta u_i(k)$. Since the amount of the resources that flows into the cell is limited, the absolute Value $|\Delta u_i(k)|$ is considered as the resource variables. Now each agent can either play the role of the consumer or the producer. A positive deviation $\Delta h_i(k)$ means that the cell "needs" some more resource to reach the required level (i.e. to allocate all calls).

$$\Delta h_i(k) = h_i - h_s > 0. \text{ i.e., } h_i > h_s \tag{4.33}$$

Thus, the related agent can be declared as a consumer, which has to acquire a certain amount of the resource. This demand of consumer *i* at instance *k* is denoted by $r_{Di}(k)$. The goal of the consumer is to maximize his utility, (i.e. by reducing the call blocking probability). $J_{Ci}(k)$ with

$$\frac{J_{Ci}(k)}{r_{Di}(k)} = \Delta h_i(k) - r_{Di}(k) * I(k) \tag{4.34}$$

The relative utility is a composition of two terms. The first term takes into account that the utility of the cell from getting some resource increases with increasing deviation $\Delta h_i(k)$. The second term denotes the consumer's expenditure (allocation) with respect to his interference I(k). Its utility decreases with increasing expenditures. The minimization of the call blocking probability $J_{Ci}(k)$ leads to the consumer's demand:

$$r_{Di}(k) = \Delta h_i(k) * \frac{1}{I(k)} \tag{4.35}$$

The demand is a function of the interference. An increasing of the interference leads to a decreasing demand. In the case of a negative deviation $\Delta h_i(k)$, the cell contains too much free resources. Hence, the related agent is considered as a producer which wants to gift this resource to the consumers with the goal to maximize system capacity/efficiency and its profit $J_{pi}(k)$, denoted by

$$\frac{J_{pi}(k)}{r_{Si}(k)} = |\Delta h_i(k)| * I(k) - r_{Si}(k) \tag{4.36}$$

The relative profit contain two terms; The first term takes into account that the utility of the producer increases with his income and with increasing deviation $|\Delta h_i(k)|$. The second term is production costs that are assumed to be proportional to the supply. The maximization of $J_{pi}(k)$ leads to the supply of producer agent *i*:

$$r_{Si}(k) = |\Delta h_i(k)| * I(k) \tag{4.37}$$

One problem occurs: *If all agents are producers or all agents are consumers.* However, there is always nominal channels/resources in the cells (nominal channel can be used only from own cell). Therefore, obviously have a permanent producer, which is independent of the amount of resource (swapping method). Assuming *n* coupled cells, the actual number of producers at the instance *k* is *m* while the actual number of consumers is *q* with $n = m + q$. Each consumer agents computes his demand while each producer agents computes his supply. All functions are transmitted to an auctioneer agent using the communication network (the auctioneer could be the distributor agent, (*D*). The task of the auctioneer is the computation of the equilibrium using the constraint that the sum of all demands has to equal the sum of all supplies:

$$r_{Dp}(k) + \sum_{i=1}^{q} r_{Di}(k) = r_{Sp}(k) + \sum_{j=1}^{m} r_{Si}(k) \quad (4.38)$$

Hence the output variables $\Delta u_i(k)$ are

$$\Delta u_i(k) = \Delta h_i(k) * \frac{1}{I(k)}, \text{ i consumer.} \quad (4.39)$$

$$\Delta u_i(k) = \Delta h_i(k) * I(k), \text{ i producer.} \quad (4.40)$$

- **Power control**

The power control can raise the network capacity. Some power control algorithms [51, 58, 80, 96] based on the idea of balancing the SIR of all radio links have been introduced, but the final SIR achieved by those algorithms may be unsatisfactory for some of the links. Some calls must be dropped in order to keep the SIR of other calls higher than the predefined threshold value. Obviously, the efficiency of radio resource management is dependent on the channel assignment and the power control. The combination of DCA and power control to obtain some substantial capacity gains has been reported in [52], however, because no channel pre-selection is done before the channel probing procedure, inadvertent dropping of calls caused by originating calls can occur so often that all unsuccessful (blocked or dropped) calls are unintentionally dropped calls and not blocked calls. In addition, an exhaustive search and too frequent intra-cell handoff access will decrease the system capacity and make the algorithms difficult to implement in real networks. Here, a cognitive radio algorithm with power control is proposed. The power that is transmitted both from the mobile equipment and from the base station has a far-reaching effect on efficient usage of the spectrum. Power control is an essential feature in mobile networks, in both uplink and downlink. When a mobile transmits high power, there is enough margin in the critical uplink direction. But it can cause interference to other subscriber connections. The power of the signal transmitted by the base station antenna should be kept to a level above the required threshold without causing interference to the mobiles. Mobile stations thus have a feature such that their power of transmission can be controlled. This feature is generally controlled by the BSS. This control is based on an algorithm that computes the power received by the base station and, based on its assessment, it increases or decreases the power transmitted by the mobile station. The signal power at the *ith* receiver is given by $G_{ii}F_{ii}P_k$ [45](see section 4.8.3), and the total interference power is given by

$$\sum_{k \neq i} G_{ik} F_{ik} P_k \tag{4.41}$$

The SIR of the *i*th receiver (or transmitter) is given by

$$SIR_i = \frac{G_{ii} F_{ii} P_k}{\sum_{k \neq i} G_{ik} F_{ik} P_k} \tag{4.42}$$

$$SIR_i = \frac{G_{ii} F_{ii} P_k}{I_i} \tag{4.43}$$

We assume that the QoS requested is provided when the SIR exceeds a given threshold SIR^{th}. The outage probability of the *i*th receiver/transmitter pair is given by

$$O_i = \Pr ob(SIR_i) \leq SIR^{th} \tag{4.44}$$

$$= \Pr ob\left(G_{ii} F_{ii} P_i \leq SIR^{th} \sum_{k \neq i} G_{ik} F_{ik} P_k \right) \tag{4.45}$$

The outage probability O_i can be interpreted as the fraction of time the *i*th transmitter/receiver pair experiences an outage due to fading. Note that the in our expression for O_i, we take into account statistical variation of both received signal power and received interference power. We now consider the market method to regulate the SIR. By ignoring all statistical variation of both signal and noise power, the signal power at the *i*th receiver is then $G_{ii}P_i$ and the interference power at the receiver is given by $\sum_{k \neq i} G_{ik} P_k$. Then the SIR at the *i*th receiver is given as

$$SIR_i^m = \frac{G_{ii} P_i}{\sum_{k \neq i} G_{ik} P_k} \tag{4.46}$$

We interpret SIR_i^m as follows: this is what the signal-to-interference of the ith transmitter/receiver pair would be, if the fading state of the system where $F_1 = \ldots = F_n = 1$. We also define

$$SIR^m = \min_i SIR_i^m = \min_i \frac{G_{ii}P_i}{\sum_{k \neq i} G_{ik}P_k} \tag{4.47}$$

Which is the minimum SIR of the system over all transmitter/receiver pairs. Like the outage probability O, the SIR^m gives a figure of merit for the system and power allocation. We define the market regulation/control method of the system and power allocation as the ratio of the market control SIR to the signal-to-interference reception threshold

$$MCA = \frac{SIR^m}{SIR^{th}} = \min_i \frac{G_{ii}P_i}{SIR^{th}\sum_{k \neq i} G_{ik}P_k} \tag{4.48}$$

There is a relation between MCA and *O*: when MCA is large (which means that the SIR, ignoring statistical variation, is well above the minimum required for reception), we should have small *O*. Let

$$\delta_i = \frac{G_{ik}}{I_i} \tag{4.49}$$

denote the channel variation. δ_i will be estimated and predicted in the proposed power control scheme. $I_i = \sum G_{ik}F_{ik}$ presents the received interference. G_{ik} is the link gain from mobile station *k* to base station *i*. Suppose, that the highest transmitted power allowed is P^{max} and that the lowest transmitted power allowed is P^{min}. The social agent that SNR oriented uses the following technique to regulate the SNR between the cells.

The proposed technique operates in the following way:

- For any cell, two tiers of cells are considered as interfering cells. The channel state information (allocating or releasing) of each cell is locally exchanged to its interfering cells. Every cell maintains a list of the cost for all channels. The cost function is used to decide the cost of a channel. The cost of a channel in a cell is updated (increased or decreased) in real time if a co-channel call is accepted or terminated (dropping and departure) in one of the cell's interfering cells.
- When a call arrives in a cell, the free channel with highest priority (lowest cost) is chosen for call set-up and the call power probing process is activated. The procedures of the power probing for a new (or handoff) call are:

1. Assigning the minimum transmitted power P_{min} to the new call p.
2. Measuring the SIR value γ_p of the call.
3. If $\gamma_p < \gamma$, adjusting the power of the call and going back to step 2; if $\gamma_p \geq \gamma$, and $P_{min} \leq P_p(k) \leq P_{max}$, this call is admitted into service with this power and the call power probing process is ended.
4. If a power cannot be found in the range of [P_{min}, P_{max}] with which the SIR value $\gamma_p \geq \gamma$, or the probing iteration number is larger than a pre-assigned value, the probing is moved to the next highest priority channel. Actually, an exhaustive searching is not allowed in a system. Hence, we prescribe that if four channels have been evaluated, but the SIR requirement is still not satisfied, the call is blocked.
5. If a call is in service, the power control algorithm is used to maintain its quality. Each base station monitors its own served calls at some time interval. We assume that all base stations are synchronized (actually the algorithm works asynchronously either). When the SIR of a call falls below the target value, the power control procedure is requested. However, if the maximum transmitted power is requested or the number of iterations of power level adjustment is larger than the allowed value, but the SIR is still below a specified value (e.g., the call dropping threshold value), the handoff procedure is requested. The "call set-up" procedure will begin to search for a channel for handoff. If a channel is found, the call is moved to this channel. Otherwise, the call is dropped.

4.9 Handoff based on CR

In this section, we study the handoff process based on cognitive scheme. The goal of the introduction of cognitive radio in handoff (section 1.6) is to reduce the repeated unnecessary handoff process within the same cell. To achieve this goal, we consider the SNR measurement and the radio coverage. In general, the user releases the channel when the user completes the call or when the user moves to another cell before the call is completed. The procedure of moving from one cell to another, while a call is in progress, is called handoff [46, 71, 95, 117, 121, 146, 149]. While performing handoff, the mobile unit requires that the base station in the cell that it moves into will allocate it a channel. The handoff call is blocked: if no channel is available in the new cell, or if the handoff procedure takes more than a predetermined time limit to complete. This kind of blocking is called handoff blocking [118] and it refers to blocking of ongoing calls due to the users.

A. The SNR Measurements

Based on the SNR measurements the cognitive radio scheme performs the handoff. As we discuss the SNR value in section 4.8.8.A, the SNR value is affected by the transmitted power and the frequency it carries. In order to obtain a criterion measurement of the received SNR, we enforce each mobile station which has packets to transmit has to use the lowest frequency to contend the channel access right during the uplink contention period with a pre-defined transmission power. The reason we consider the channel of lowest frequency as the contention channel is that we want to ensure that the mobile station can communicate with the base station even if it is in the boundary of the macro-cell since the lowest frequency can get the maximum transmission distance. The base station, after receiving a RNG-REQ message from the mobile station, calculates the estimated distance between the base station and the mobile station according to the received SNR value. Assume the BS needs a necessary received minimum power or sensitivity $P_{r,min}$ from each mobile station, which corresponds to a minimum required SNR value denoted as $SNR_{r,min}$, to successfully receive the signal [126][137]. Then, according to

$$P_r[dBM] = 10\log(P_r[mW]) = P_t + G_t + G_r - PL(d) - L \qquad (4.50)$$

and $SNR(dB) = P_r(dBm) - N_0(dBm)$. We have

$$SNR_{r,\min} = P_{r,\min} - N_0 = P_t + G_t + G_r - PL(d) - L - N_0 \qquad (4.51)$$

Substituting the next equation in equation (4.43)

$$PL(d) = PL(d_0) + 10\rho\log\left(\frac{d}{d_0}\right) + X_\sigma + C_f + C_H \text{, d} \geq \text{d}_0 \qquad (4.52)$$

We receive the following equation

$$SNR_{r,\min} = P_t + G_t + G_r - 20\log\left(\frac{4\pi d_0 f}{c}\right) - 10\rho\log\left[\frac{d}{d_0}\right] - X_\sigma - C_f - C_H - L - N_0 \qquad (4.53)$$

Where the term PL(d_0) is for the free-space PL with a known selection in reference distance d_0, which is the far field of the transmitting antenna (typically 1 km for large urban mobile system, 100 m for microcell systems, and 1 m for indoor systems) and is measured by PL(d_0) = 20log(4πd_0/λ). X_σ denotes a zero-mean Gaussian distributed random variable (with units in dB) that reflects the variation in average received power that naturally occurs when PL model of this type is used. ρ is the path los exponent, where ρ =2 for free space, and is generally higher for wireless channels. C_f is the frequency correction factor, accounts for a change in diffraction loss for different frequencies which a simple frequency dependent correction factor C_f due to the diffraction loss. C_H is the receiver antenna height correction and *h* is the receiver antenna height.

B. Signal Positioning

In this section, we illustrate the radio coverage prediction [R6] by introducing a case study was undertaken for a radio network planning [72] using NIR-PLAN[2] (see appendix B) in 10 km^2 of Haifa (Israel) as illustrated in Figure 24. This study in an urban environment concludes that a conventional propagation model could lead to erroneous planning with less than expected quality of service, unacceptable interference, and more base stations than necessary. Using the NIR-PLAN, the radio network designer can reach optimal levels for the base station deployment and configuration while meeting the expected service level requirements. This can be done with the help of propagation models, geographical information, filed data and optimization algorithms, which are integrated in the planning tool. For instance, case of a CDMA based radio technology provides the required orthogonality between users at the cost of accurate power control, some restriction in code allocation, and limited cell range depending on the interference level. Since the interference level depends on the activity of all other users and on their allocated power, the cell range depends on the traffic and power distribution in the cell. This well-known cell breathing effects lead to an

[2] Hexagon System Engineering Ltd

iterative approach to compute the power allocated to each user and the level of interference. These computations depend directly on the user locations and on the services (data rate) used. Thus, CDMA radio network planning is performed through simulations of a user and service distributions. In a network simulation, the users and their service (data rate) requirements are spread over the area under investigation. The required power and the interference are computed iteratively for each user. In order to meet the requirements of the mobile services, the radio network must offer sufficient coverage and capacity while maintaining the lowest possible deployment costs. As we mentioned in the previous section, the network in a cellular network is divided into many cells, and usually a base station is deployed in the center of each cell. For the sake of easy analysis, the cells are represented as neighboring hexagons, while in reality they can be of any kind of forms and overlap with each other. The size of each cell, when fixed, will usually stay stable. Unlike the CSMA system described above, there is one important feature in GSM network planning: the coverage planning and capacity planning are independent. The coverage planning depends on the received signal strength, that is to say, the covered area is nearly only limited by the minimum signal strength at the cell range, while the later capacity planning depends mainly on the frequency allocation.

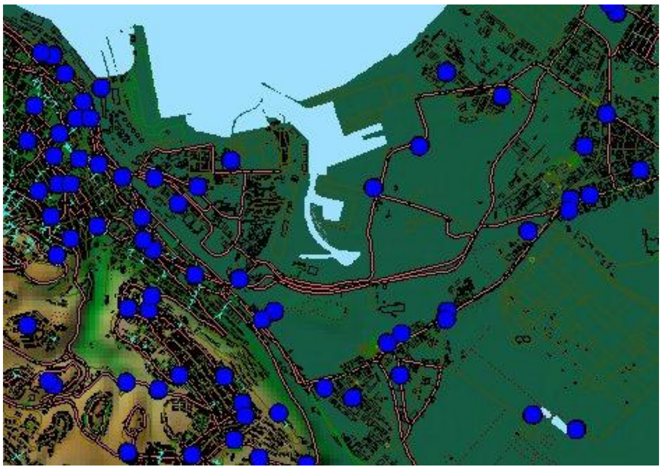


Figure 24: Base station site

Figure 25 illustrates a three-sector antenna pattern that is clearly seen from the shape of the results. This Figure 25 shows the deployment in the suburban of Portland, and it shows the coverage sectors, wherein the colors represent the frequency channel used for each sector. This plan is for a WiMAX system- a system considered to be the precursor of fourth generation of cellular networks. In a WiMAX system, orthogonal planning, like GSM, and non-orthogonal planning like that of CDMA networks, can be combined. Hence, we see the same channel is allocated to neighboring sectors and the interference between them should then be mitigated by other means.

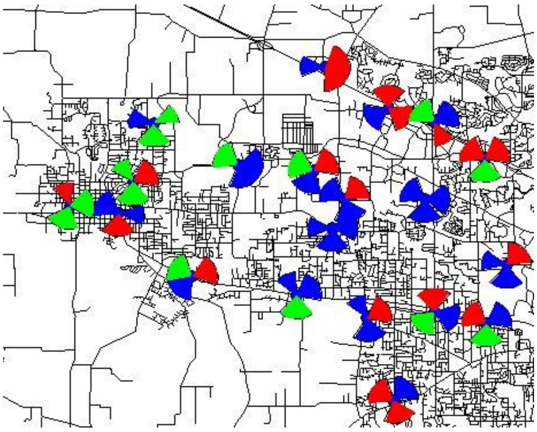


Figure 25: Base station deployment and frequency plan

Figure 26 shows the results of the base station transmission and the effect of streets and the impact of the building on the propagation. The different colors in the pictures represent the coverage area of three base stations (shown as blue dots with a number next to them). The yellow color represents the area where the signal arriving from station 1 is strongest, green is from station 4 and red for station 5. Stations 2 and 3 are not shown in the picture, still there are some points where their signal is strongest and can be seen colored in pink or blue.

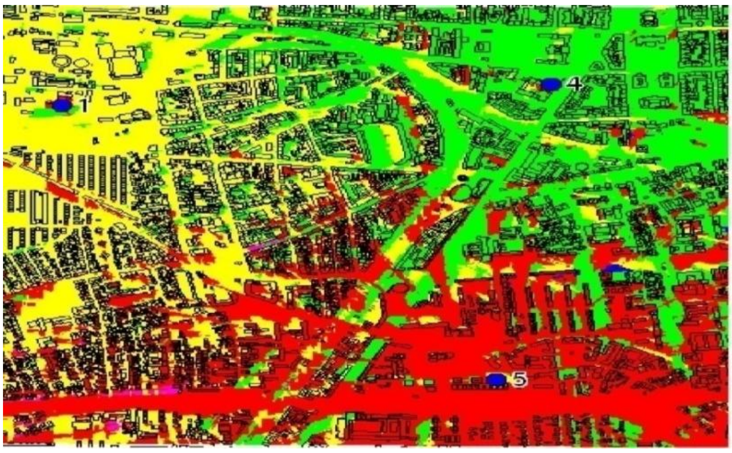


Figure 26: Signal strength

The goal of illustrating the Figure 26 is to illustrate that the cell receives a several signal powers from neighbor cells. This issue will be handled again in next section by introducing the handoff process and the unnecessary repeated handoff process.

C. Handoff process

Interference in the radio channel reduces the quality of the transmission. There are different quantities that measure the quality as signal-to-interference ratio (SIR) and the bit-error rate (BER). SIR, referred to also as signal-to-interference-and-noise ratio (SINR) to emphasize the presence of background noise, is the ratio between the power of the desired signal and the power of the interference (plus noise). BER indicates the error rate in the decoded information sequence after the demodulation of the incoming signal. In different systems, several quantities are used to describe the desired signal and interference ratio. All are closely related to SINR. For example, for code division multiple access (CDMA) systems, the bit energy-to-interference-and-noise-spectral-density (E_b/N_0) is SINR multiplied by the number of information bits modulated by the spreading code, whereas the carrier-to-interference-and-noise-power ratio (CIR or C/I) is equal to (E_b/N_0) divided by the length of the spreading code. It must be noted that the difference between the quantities are just in the scale. In order to test our algorithm in a practical interference scenario in cellular networks, we consider a handoff scenario. Furthermore, we consider a set of *L* cells, each containing one base station. Furthermore, several mobile stations are allocated to one base station. The interference scenario that occurs in the cellular system [R5] which we will deal with is described below.

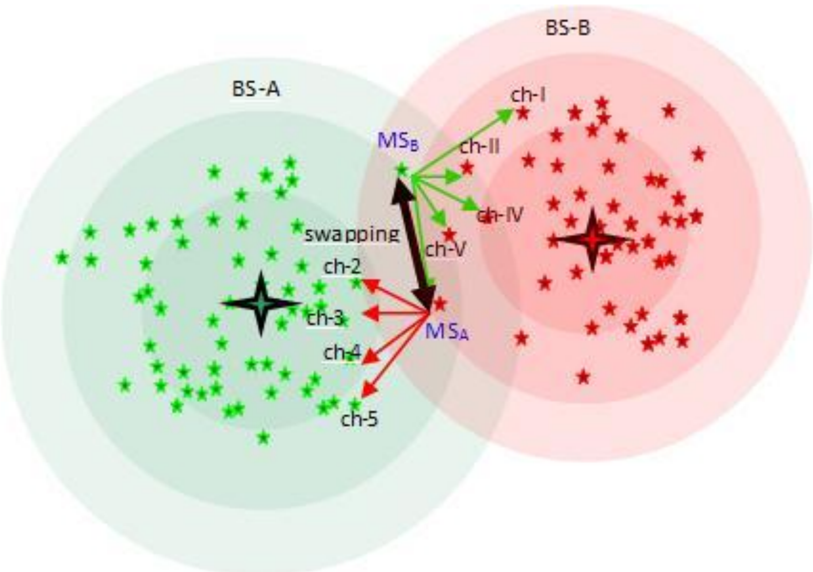


Figure 27: Channel mutual interference

In Figure 27, two different mobile radio systems are illustrated. Mobile station MS_A is located at the cell boundaries of system *A*, however very close to base station BS-*B*. At the same time, mobile station MS_B is served by base station BS-*B*, and is located very closed to base station BS-*A*. Interference may occur at base station BS-*A* from mobile station MS_B and at mobile station MS_B from base station BS-*A*. The same interference will be introduced at base station MS-*B* and at mobile station MS_A. In this section, we deal with the case of the mutual interference which occurs between the base station and the mobile station as illustrated in Figure 28.

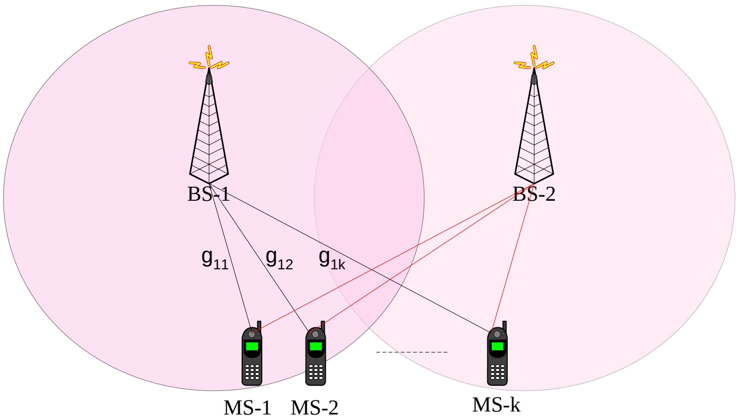


Figure 28: BS-MS interference

To overpower the path loss issue that is defined as the local average received signal power relative to the transmit power, the iterative swapping prediction scheme can be extended in order to use it in the handoff Management [113]. In our case, the handoff is started when the received power is weak and less than a given target value SNR^{tgt}. As described in Figure 29, the handoff carried out when the mobile host (MH) receives a weak SNR from BS-*A* and at the same time a strong signal from the neighbor BS, i.e.

$$SNR_A^{tgt} > P_r > SNR_B^{tgt} \tag{4.54}$$

Where P_r is the received power signal at the MH location, in other words the handoff strategy is designed as follows: At first, we track the change of the SNR of current channel. When the SNR is above threshold SNR^{tgt}, handoff will not occur. If the SNR is below threshold SNR^{tgt}, we will begin handoff execution immediately. Otherwise, when the SNR is between the two thresholds, we will use our handoff initiation algorithm to make a decision. The adaptive agent makes a decision, whether mobile host (MH) should handoff or not, based on the combination of several parameters, e.g. SNR and system load, in order to avoid repeating or performing unnecessary handoffs. In addition, the system load is used to decrease the handoff dropping probability and provide QoS guarantee.

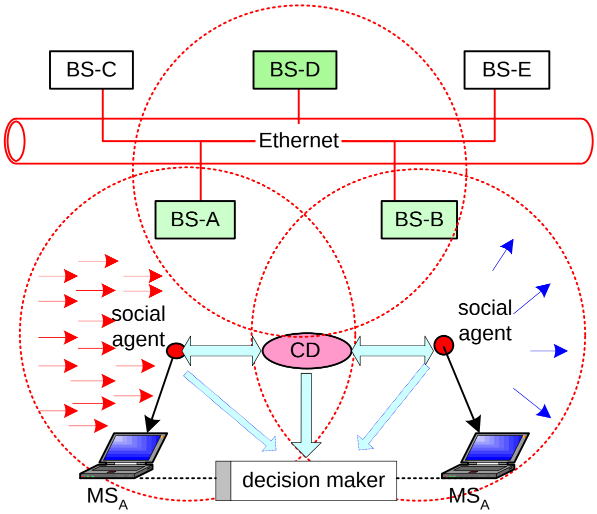


Figure 29: Handoff process

- **Simulation Results**

This section uses the methods presented in previous chapters to implement simulation scenarios focused on handoff process in cellular systems.

In cellular systems, each base station transmits a beacon Signal, and a mobile station selects the base station with the strongest received power. This way causes a repeated unnecessary handoff in the same cell. To avoid the repeated unnecessary handoff in the same cell, we have introduced the cognitive radio approach based power transmission (section 4.8.9) that control and manage the power in the cell. The handoff process starts according to the algorithm based SNR (section 4.8.9). Without loss of generality, we introduce handoff scenario with two base stations from whole cellular system. Due the social agents behave similar and uses the same functions and the same rules in all base stations in the cellular system. Due to the autonomy of the social agent that manages the base station. We describe two base stations in the handoff process. Furthermore the social agent decision is based on the calculation and measurements.

The number of the mobile stations that move from cell to cell is not relevant. Because the social agent manages the cell and takes place in the base station and it makes the decision for the mobile station when to start the handoff process. From this view point, the number of the base stations in the scenario is not important, because the social agent behaves the same in the all cells. Furthermore the distributor provides the cells with ensure information about the channel state (free/ busy channels). After that the social agent communicates with one neighbor cell when it needs to acquire a free channel. Hence the number of the exchanged messages between two cells is reduced and the cell is less over loaded.

Figure 30 describes the handoff scenario [R5] which we have implemented in an OPNET modeler [111]. There are two BSs *A* and *B* connected to each other via switch node. The BS has its own coverage, which is about 500 meters according to the standard. Moreover, the mobile host (STA) moves continuously during the simulation from BS *A* to BS *B*. In order to make the handoff scenario more clearly and to make it more comprehensible we introduce the Figure 31. The goal of the implemented scenario is to ensure that the SNR plays an important role for reducing the handoff latency and the interference respectively. Accurate signal reception is possible only when the relation of energy per bit E_b to noise spectral density N_0 is appropriate. Low value of E_b/N_0 will cause the receiver to be unable to decode the received signal, while a high value of the energy per bit in relation to noise will be perceived as interference for other users of the same radio channel.

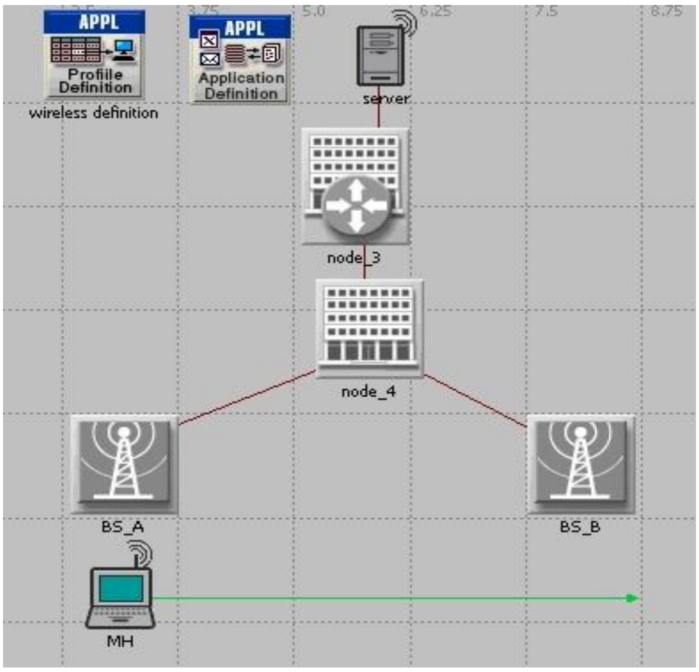


Figure 30: MS handoff

Figure 31 describes the base station more deeply. The base stations are sectorized antenna that propagates in three directions. Each base station consists of three sectors.

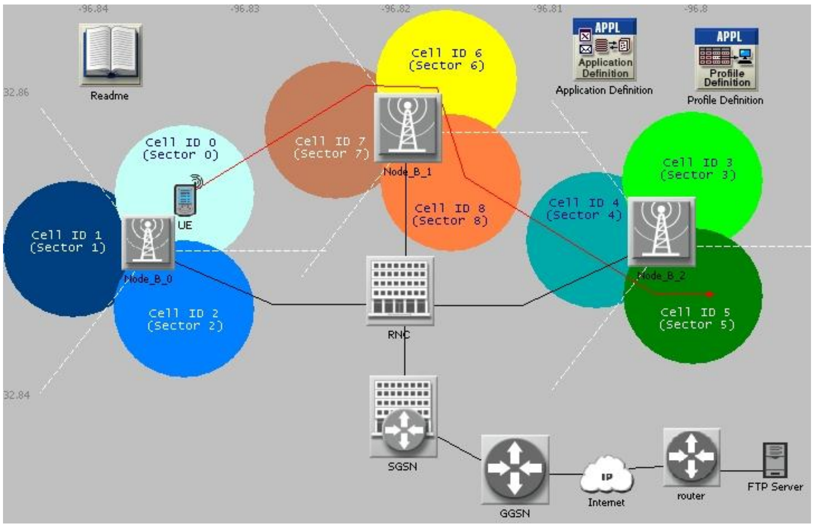


Figure 31: Handoff with sectorized antenna

Figure 32 describes the average of the uplink actual E_b/N_0 in base station *A* and base station *B*.

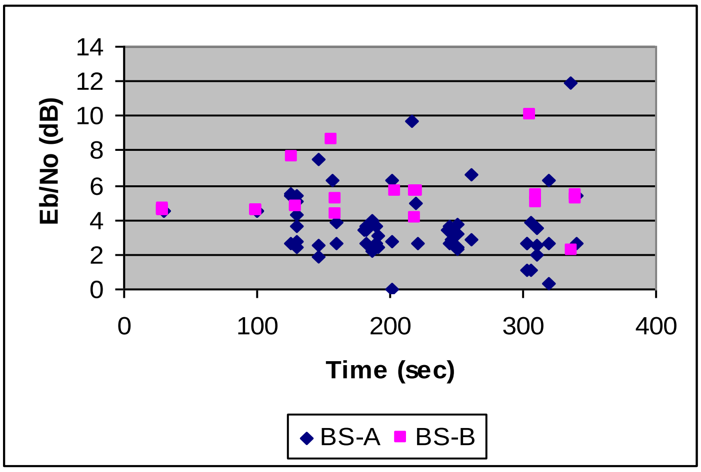


Figure 32: Uplink actual E_b/N_0 (dB)

The change of the SNR is caused mainly by the movement of the mobile host, as shown in Figure 33. The horizontal axis depicts simulations run time in seconds and the vertical axis depicts the SNR in dB. The SNR is referred to distance (mobile station position in the cell). The mobile station moves randomly, and the channel fading will decrease and increase with the distance changes between the mobile host and the BS. From the Figure 33 we can see that the SNR of the two BSs changes up and down. In the base station *A*, the mobile station follows the strongest received power signal. In this case, the mobile station selects the base station whose transmitted beacon power is most strongly received. This causes that a few channel are highly requested, and some channels are never used. On other side the mobile station in base station *B* start the handoff based on the agent's decision that manages base station *B*. The decision takes into consideration the received SNR from the neighbor cells. Hence the social agent regulates the SNR in cell *B* with collaboration with the SNR in neighbor cells.

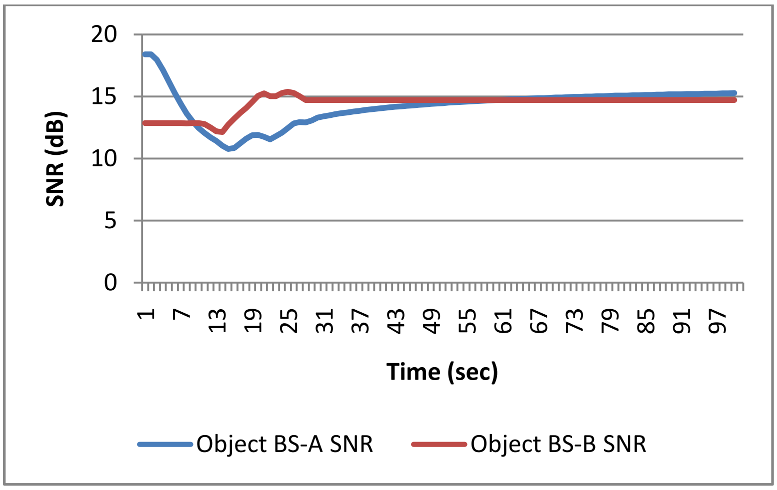


Figure 33: Handoff process based SNR

Figure 34 describes the end-to-end delay that is caused due to the repeated unnecessary handoff in the same cell. The handoff process in conventional scheme (DDCA) needs more time in order to be finished. In the conventional approach the mobile station needs many times to move to next neighbor cell. Because based on conventional scheme the mobile station follow the strong SNR. The social agent in the cognitive radio scheme prevents the repeated unnecessary handoff, for this the handoff delay in cognitive radio is less.

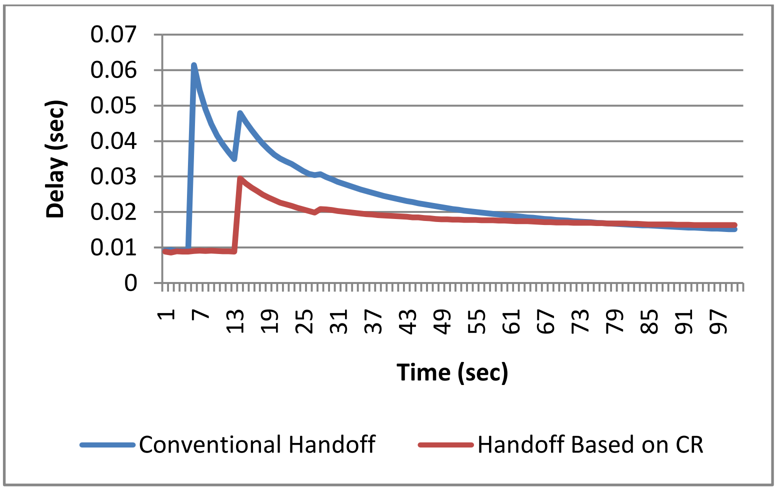


Figure 34: End-to-end delay

To discuss the effect of the channel capacity and the throughput based on SNR, we consider the Shannon formula [132]. The capacity of the channel is given by the next equation.

$$C = W \log_2\left(1 + \frac{S}{N}\right) \tag{4.55}$$

Where W is the channel bandwidth in Hertz, C is the channel capacity in bits per second, S is the signal power, and N is the noise power. Equation (4.55) provides the relationship between the theoretical ability of a communication channel to transmit information without error for a given signal-to-noise ratio and a given bandwidth of the channel. The channel capacity can be enlarged by increasing the channel bandwidth, the transmitting power, or a combination of both. The repeated unnecessary handoff in the same cell decreases the channel capacity and the throughput as illustrates Figures 35 and 36. Figure 35 describes the comparison of two systems throughput in handoff process. One of the systems applies a conventional handoff (DDCA). Another one is based on the cognitive radio scheme. A successful handoff can decrease the number of conflicts especially in heavy traffic. When conflicts occur, the packets will be retransmitted and if the number of retransmitted packets reaches the maximum, the packet has to be discarded. Furthermore Figure 36 illustrates that the mobile station starts to transmit packets after few time interval.

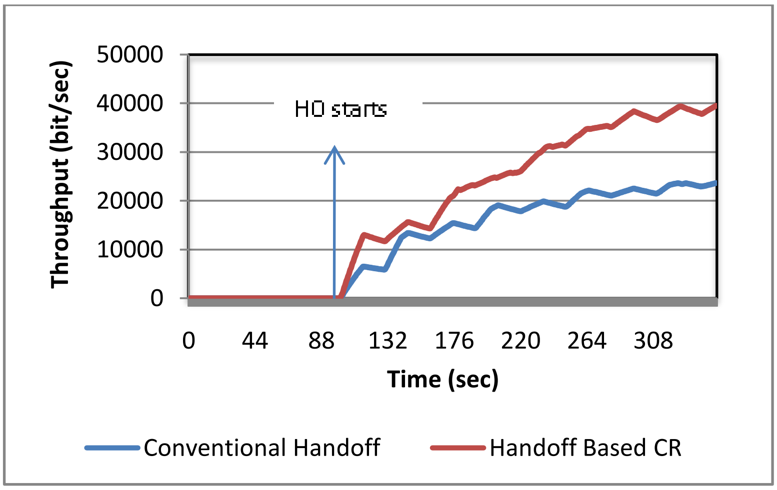


Figure 35: Comparison of two systems throughput

Figure 36 illustrates that the cognitive radio scheme improves the throughput, which is the number of packets transmitted successfully. Now we rewrite the equation (4.55) in terms of E_b/N_0 directly using the relations $S = E_bR$ and $N = N_0W$. We then get the following equivalent expression for the Shannon capacity

$$\frac{C}{W} = \log_2\left(1 + \frac{R}{W}\frac{E_b}{N_0}\right) \tag{5.56}$$

The expression relates the three parameters C/W (normalized capacity), R/W (normalized transmission rate), and E_b/N_0. The Shannon capacity expression (5.56) gives is the smallest possible value required of the signal bit energy E_b at any capacity level. The minimum energy increases as the capacity, normalized to the bandwidth, increase.

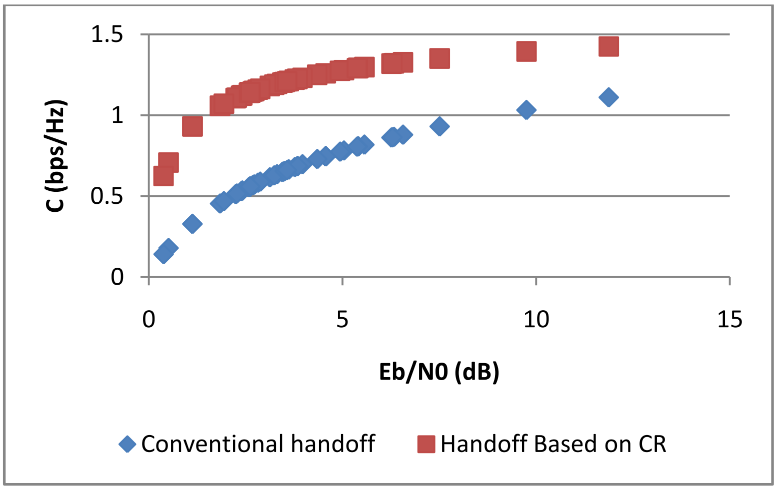


Figure 36: Bandwidth efficiency

Figure 37 describes the relationship between the blocking probabilities versus E_b/N_0 in cognitive radio scheme. Based on the introduced scenario, we conclude that the repeated unnecessary handoff in the same cell causes a delay that reduces the channel capacity and increases the call blocking rate in handoff.

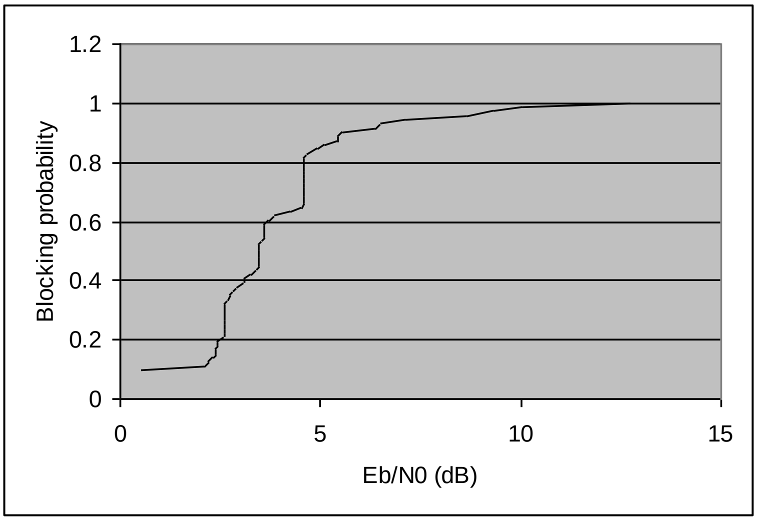


Figure 37: Blocking probability

D. Cell Load

In this section we describe the social agent behavior in the cell that stand under heavy traffic load as illustrates Figure 38.

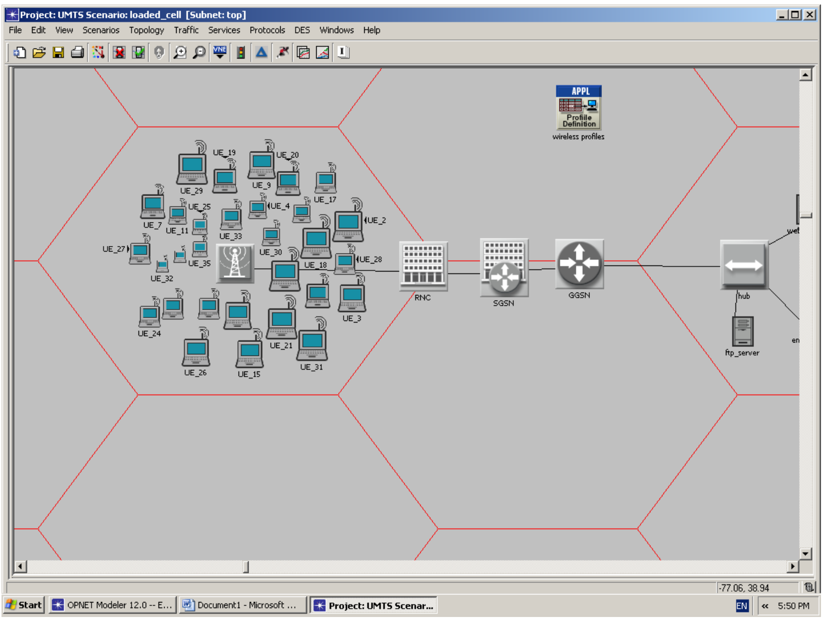


Figure 38: Heavy traffic loaded cell

The more traffic generated the more base stations will be needed to serve the users. The number of base stations for a simple cellular network is equal to the number of cells. We consider traffic load as an important factor for initiating handoff. The traffic load can seriously have an effect on quality of service for users, thus it requires efficient management in order to improve service quality. The repeated unnecessary handoff in the same cell sets the cell under heavy traffic load. This reason is enough to increase the traffic load in the cell. In order to avoid the cell load that is caused by repeated unnecessary handoff in the same cell we introduce the cognitive radio scheme. The cognitive radio ensures that the system is not overloaded and guarantees the needed quality of service requirements. The cognitive radio scheme is specially developed to effectively manage overloaded traffic in these systems and avoid too early or too late initiation of the handoff process. In the cognitive scheme, based on the negotiation between agents that are managed the cells and the distributor that is managed the cluster (section 4.2-4.3), we can reduce the cell load the cellular system by managing the traffic load the system. In this section, we compare the cognitive radio scheme to the distributed dynamic scheme in a cell which it is under heavy traffic load. Generally, the increase in the load traffic increases the call blocking rate. Furthermore, the more loading is allowed in the system, the larger is the interference margin needed in the uplink, and the smaller is the coverage area (section 4.9.B). For coverage-limited cases a smaller interference margin is suggested, while in capacity-limited cases a larger interference margin should be used. In the coverage-limited cases, the cell size is limited by the maximum allowed path loss in the link budget, and the maximum air interface capacity of the base station site is not used. Typical values for the interference margin in the coverage-limited cases are 1.0□3.0 dB, corresponding to 20 ↕ 50% loading.

Figure 39 illustrates the comparison between the cognitive radio scheme, and the distributed dynamic channel allocation scheme related to the throughput under a loaded cell. The cell stands under heavy traffic load when several mobile users demand free channels in a cell. In this case the mobile user should wait in the queue till a free channel is available. The mobile user used the available channel till a new handoff occurs. A lower throughput and capacity in the system degrade the quality of service parameter (throughput). Furthermore Figure 39 shows that the throughput in the cognitive radio is bigger than the throughput in DDCA. The cognitive radio acquires the channel faster than the DDCA. In the DDCA the repeated unnecessary handoff in the same cell increases the load in the cell.

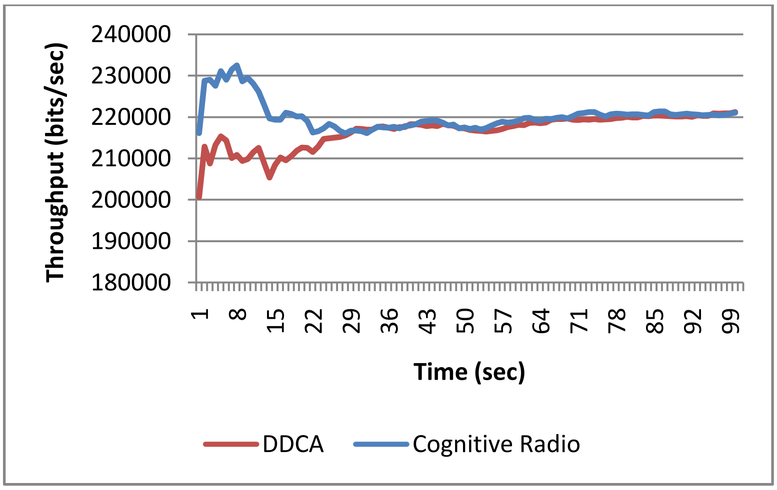


Figure 39: Throughput under loaded cell

Figure 40 shows that the number of the requested granted resource in cognitive radio is higher than in distributed dynamic channel allocation scheme, because the repeated unnecessary handoff in the same cell in the distributed dynamic channel allocation scheme causes a higher delay than the delay in the cognitive radio scheme. For that the resource acquisition delay in the distributed dynamic channel allocation scheme is higher than in cognitive radio as Figure 41 illustrates. The higher delay in the cellular system causes call blocking or call dropping mostly. In other words, the proposed cognitive radio scheme supports high quality compared to distributed dynamic channel allocation.

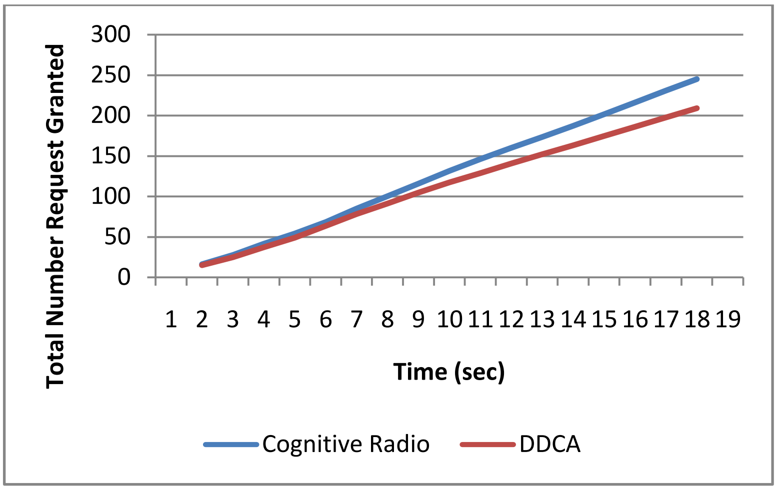


Figure 40: Number of the requested granted resources

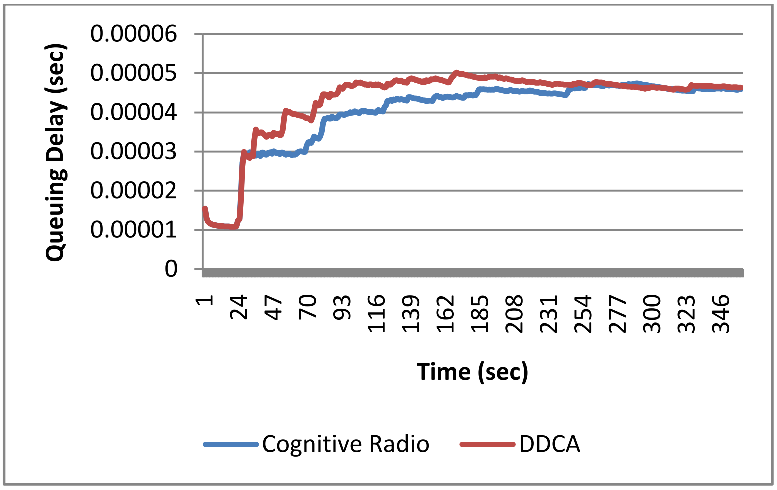


Figure 41: Queuing delay

E. Handoff of several MSs

We consider the scenario that we have more one mobile stations e.g. several mobile stations in the cell (BS-A) that will handoff to neighbor cells (BS-B and BS-C) as illustrates Figure 42. The second mobile station (MS2) can start the handoff process without to wait till the first mobile station (BS-A) finished its handoff process. Because the social agent takes into account that handoff latency should be zero otherwise the call will be blocked. In other words, the handoff process will carry out automatically when the SNR become a weak. Figure 42 describes three mobile stations BS (MS1, MS2, MS3) that will handoff to neighbor cells (BS-B, BS-C). The following figures describe the behaviors of the node B. The node B consists of three sectorized cells. The social agent decision is based on the information from the distributor about the available channels in neighbor cell. The mobile station moves to the neighbor cell that has the highest number of free channels.

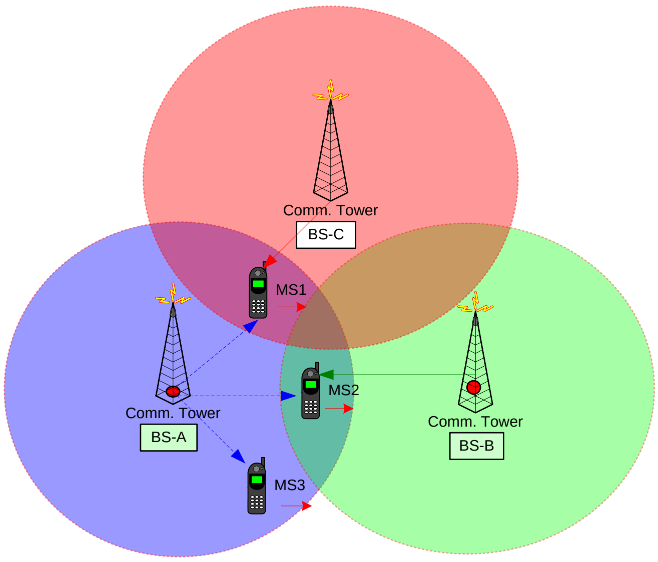


Figure 42: Handoff process of mobile stations

Figure 43 shows the mobile stations moving from one BS-A to another BS-B and BS-C. The mean signal strength of BS-A decreases as the mobile station moves away from it. Similarity, the mean signal strength of BS-B increases as the mobile stations approaches it. The critical zone as shows figure 43 is covered from two base stations. Figure 46 illustrates that the mobile station in the critical zone (zone A) can receive different signal strengths. (see equation 4.54).

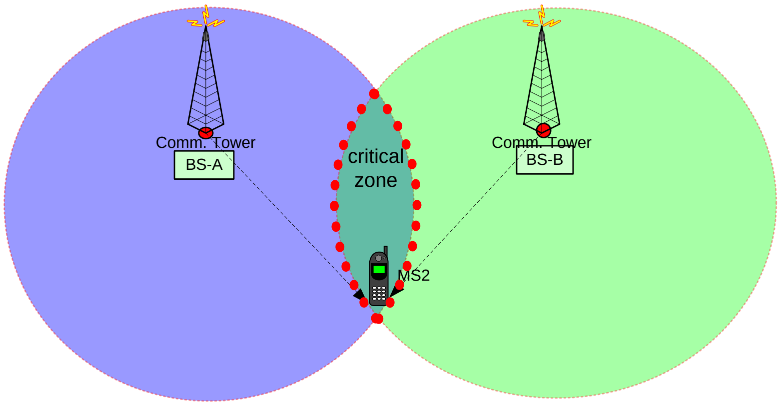


Figure 43: Critical zone

When the mobile station (MS2) receives weak signal strength from BS-A, the mobile station informs the BS-A and it start the hand off to neighbor cell. The BS-A starts to computes the SNR, only when the mobile station arriving the critical zone. In other hand it not necessary to compute the SNR when the mobile station (MS2) moves within the home zone (BS-A). A handoff is generally performed when the quality of the link (measured in terms of the power of the received pilot) between the Node B and the mobile station on the move is decreasing and it is possible to hand off the connection to another cell with better radio characteristics. The required signal power density below the interference power density before despreading is designated as SIR (Signal to Interference Ratio), and it is also known as Ec/Io (In fact, Ec/Io and Ec/No are the same thing. The Ec/No denote the Energy per Chip (Ec) to Noise Spectral Density (No) ratio for one user. Based on the downlink power measurement reported from each Node B, it will be determined whether the addition of the radio link is acceptable or not. A mobile station, during a call, de-modulating signals from three BTSs, Figure 44 and figure 45 illustrate that when the quality of the radio link decreased then the mobile station handed off. Figure 45 illustrates that the quality of the radio in cell 1 starts to decrease after 35 sec, and in cell 0 after 55 sec starts the quality of the radio to decrease, and in cell2 after 75 sec starts the quality of the link to decrease. The decreasing of the quality of the radio is expressed in the deceasing of the total downlink throughput as illustrated in Figure 45. Some places in the cell (cell boundary/critical zone) are covered from several neighbor cells. The mobile station strategy is to follow the best quality of the radio link. Figure 44 shows that the mobile station 1 is initially de-modulating traffic channels from the base station *A* but it measures another channels from neighbor cell *C* and verifies that its strength (E_c/N_0) exceeds the (E_c/N_0) target, the mobile host exchanges messages with distributor and requesting a handoff. Figure 44 illustrates the Ec/N_0 for once cluster that consists of 3 cells related to the Time.

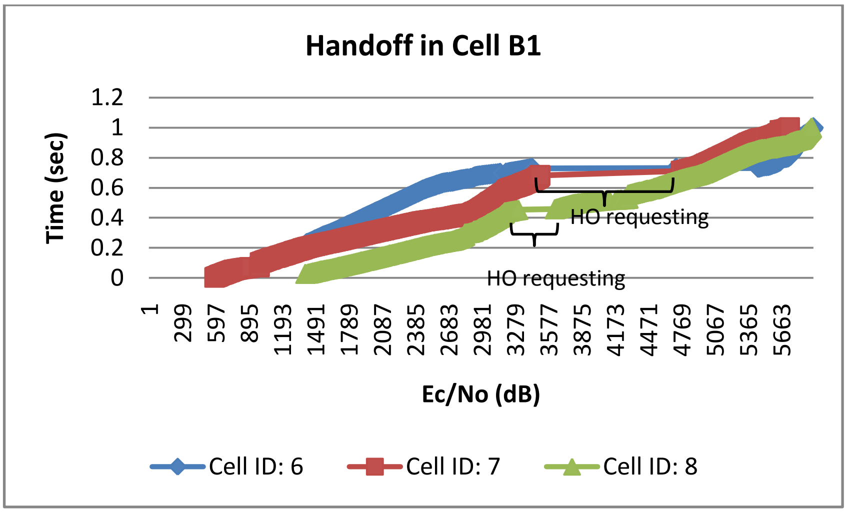


Figure 44: UE handoff pilot channel Ec/N0 (dB)

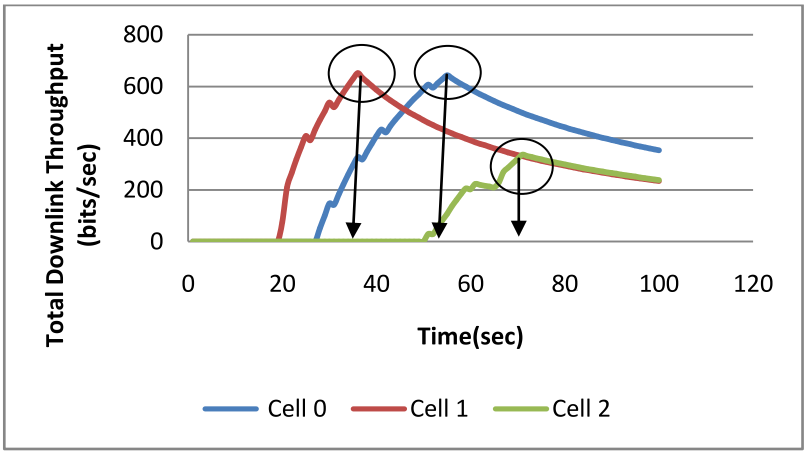


Figure 45: Total downlink throughput

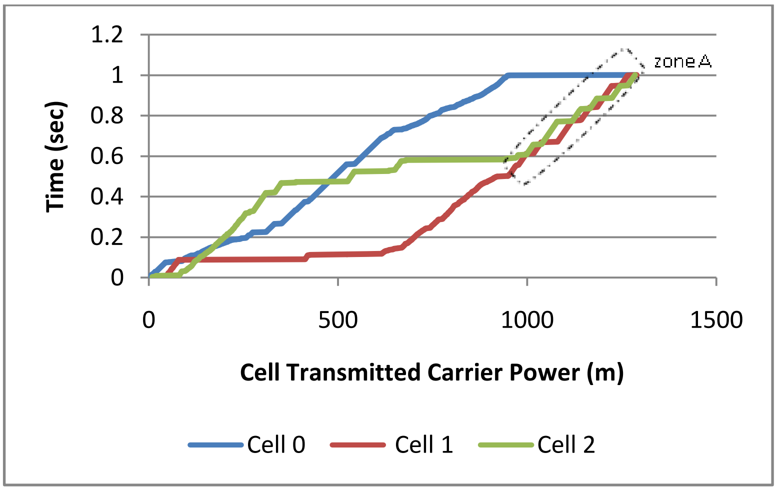


Figure 46: Cell transmitted carrier power

5 Evaluation of cognitive radio approach

Several channel allocation schemes have been introduced in cellular system, to meet the new mobile services requirements. Generally, the deficiency of the proposed channel allocation strategies are that they are developed to deal a specific issue in the cellular systems. And most of the solutions proposed have an entirely reactive approach: the response to a series of events follows an algorithm that is designed to react to a specific situation, this limits their efficiency. For instance, the uplink and downlink direction are strongly coupled in a TD–CDMA/TDD interface if asynchronous time slot overlaps occur. Therefore, an isolated treatment of either direction may produce unrealistic results. In the fixed channel allocation schemes, a number of channels are assigned to each cell according to some reuse pattern, depending on the desired signal quality. The proposed fixed channel allocation schemes are simple, however, they do not adapt to changing traffic condition and user distribution. In order to overcome these deficiencies of fixed channel allocation schemes, dynamic channel allocation strategies have been introduced. In dynamic channel allocation, all channels are placed in a pool and are assigned to new calls as needed such that the CIR_{min} criterion is satisfied. To improve the dynamic channel allocation, strategies have been implemented in centralized and distributed. The channels in the proposed centralized dynamic channel allocation schemes are assigned by a central controller, whereas in the distributed dynamic channel allocation schemes a channel is selected according to update or search algorithms. In other words, the distributed channel allocation is based on local assignment without involving a central controller. The proposed dynamic channel allocation schemes provide flexibility and traffic adaptability. However, the main deficiency of the proposed dynamic channel allocation scheme is less efficient than fixed channel allocation scheme under high load conditions. Due to the high message complexity and high channel acquisition time in dynamic channel allocation schemes, the call blocking rate is increased under heavy load traffic. The proposed channel allocation schemes that are introduced for increasing the efficiency spectrum, are assuming homogenous hexagonal cells. Furthermore, the allocation schemes focus on the channel assignment problem central to the second generation mobile communications that cannot offer an effective solution to deal the new mobile service requirements. The real-time communication demands low delay (equal zero). However, some global optimization tools in cellular networks are used. This kind of global optimization is resource consuming, expensive, and requires a few hours to optimize a medium-sized cellular network. In other words, it is difficult for current cellular networks to react in real time to the users demands and optimize the networks. To fulfill the user's preferences and to improve the performance of the network, we introduce our approach based on cognitive radio. The proposed cognitive radio approach handled more than one area that effected the channel allocation in the cellular systems. Simulation results based on implementation of the cognitive radio in OPNET have shown better results compared to other channel allocation strategies. The comparison performed between the handoff based cognitive radio schemes to handoff based distributed dynamic channel allocation schemes. In the distributed dynamic channel allocation schemes, the mobile station selects the base station whose transmitted beacon signal is most strongly received. That causes a repeated unnecessary handoff in the same cell and it increases the delay. In addition, a few channels are high requested and some channels are never used. However, to avoid the repeated unnecessary handoff, the handoff based cognitive radio scheme is performed according to the social agent's decision and rules (section 4.8.9). The social agent in the cell behaves autonomy without any influence of the neighbor cells. The social agent manages the resource in the cell. The social agent will be informed about the resource states (free/ bust channels) from the distributor before it starts to communicate with it neighbor cell. Furthermore, we have illustrated the radio cover implemented by radio resource NIR-plan. We have handled the cognitive radio scheme from theoretical to practice. The agent approach in the cognitive radio approach is deadlock free. The cell in cognitive radio cannot wait indefinitely, because the negotiation between two cells is controlled and managed by the cluster distributor. When a cell needs to acquire a new channel, the distributor informs the cell about the channel state in its neighbor cells. After that the cell takes contact to the neighbor cell that has a highest number of available channels. For that, every cell sends a response message to request message. Hence, in finite time (defined time) a cell receives all the response messages and either it is successful in acquiring a channel. Hence, the deadlock occurred when all the cells were involved in cyclic waiting. In the system cannot occur the deadlock, because the cells by resource acquisition have not any priority to the channels in neighbor cells. Furthermore the social agent makes its decision concerning the channel lent independent to the neighbor cells. i.e. The first cell that requests the resource, the first that can use the resource. This argument can be extended to show that there can be no cyclic waiting involving any number of cells. In the cognitive radio scheme, the social agent manages the channel assignment in the cell and it is placed in the base station [R7]. In order to reduce the message complexity (the number of channels that exchanged between two cells) between the agents for updating its local information, we have assigned a distributor for each cluster to inform the agent about the channel sate in the each cell. The distributor observes the channel allocation the cluster in order to avoid the co-channel interference within distance of two cells, and the adjacent channel interference that is result of the splatter of modulated RF signal into adjacent channel. The proposed agent-based negotiation in cognitive radio helps to meet the increasing demand for wireless application, the insufficiency of spectrum is more and more serious; on the contrary, the utilization of some licensed spectrum is always low. In order to increase the spectrum utilization, cognitive radio is proposed for unlicensed users to access the spectrum unoccupied by the licensed users. In this thesis the cognitive radio schemes deals more one issues in the cellular systems and at the same time performed an improvements compared to others proposed channel allocation schemes.

6 Conclusion and Future Work

Flexible use of resources is one of the most important requirements in the next generation of mobile communications. Methods for increasing the flexibility of the network to deal with new services and traffic characteristics are a requirement and an implementation challenge. The aim of the work in this thesis was to provide more autonomy and flexibility to base stations in order to improve their means of radio resource acquisition. In addition, the autonomy to base stations helps the base stations to deal with the new service challenges in a more distributed form. The approach proposed by the author to achieve this aim, was to use cognitive radio schemes to control the channel assignment in the cellular systems. The performance of a cellular network using the cognitive radio was compared with the conventional cellular network using fixed channel allocation and dynamic channel allocation. The simulation results based on OPNET demonstrated that the use of cognitive radio scheme brought more flexibility in obtaining extra radio resources to the network than the other approaches. Overall, the cognitive radio scheme proved to be feasible and efficient. The social agent negotiation was an important feature of the system in order to improve perceived quality of service and to improve the load balancing of the traffic. Furthermore, in this thesis, we have applied the channel assignment scheme based on the cognitive radio in NIR-Plan as a practice instance for urban area. Currently, the proposed scheme has been dealt with the call blocking rate that was caused by interference. There is another important reason that increases the call blocking probability in cellular systems. The delay is a major factor that increases the call blocking probability in the cellular systems. The delay is caused by setting the request message for a free available channel in the queue. By dealing with the queue in the future work, it is important that the proposed cognitive radio schemes takes call arrival rate in the cell into account, as well as holding time, waiting time, queue length and the service time in the queue. In some application fields like real-time communication, tele-medicine service and industrial automation, it is needed to ensure a seamless and lossless latency in handoff. In other words, the latency the handoff process should be zero. In order to reduce the delay in the whole system we suggest canceling the message exchange between the social agent and the distributor. In the way that the mobile station informs the base station which channel is assigned. Hence the social agent can update its local information about the channel states in the cell and about the position of the mobile station.

Furthermore it is recommended to study the channel capacity, the performance of the social agent and how it affects the spectrum efficiently when the social agent behaves more flexible by dealing the SNR requirements. In other words to extend the social agent functions so that a radio that can change its transmitter parameters based on interaction with the environment in which it operates without to occur mutual interference with resource in neighbor cells. Those issues should be considered in the future work to improve the service quality with respect to mobility management. In this work we have presented and handled scenarios in handoff that show that the cognitive radio can avoid the repeated unnecessary handoff. In the work we have focused on the handoff process, because the handoff has been considered an important issue and a great challenge in the cellular system.

Appendix A

- **General**

Today the field of computer networks all over the world has entered an exponential growth phase. These demands have made the necessity of capable network engineers extremely covet. It is therefore crucial for universities to offer networking courses that are both educational and up to date. Due to different obstacles it is unpractical for a university to be able to offer several types of networks to its students. An invaluable tool in this case consists of the network simulator OPNET Modeler that offers the tools for model design, simulation, data mining and analysis for, considering the alternatives, a reasonable cost. OPNET Modeler can simulate a wide variety of different networks which are link to each other. The students can therefore just by sitting at their workstations exercise various options available to network nodes and visually see the impact of their actions. Data message flows, packet losses, control/routing message flows, link failures, bit errors; etc can be seen by the students at visible speed. This is the most cost effective solution for universities to demonstrate the behavior of different networks and protocols.

- **Overview**

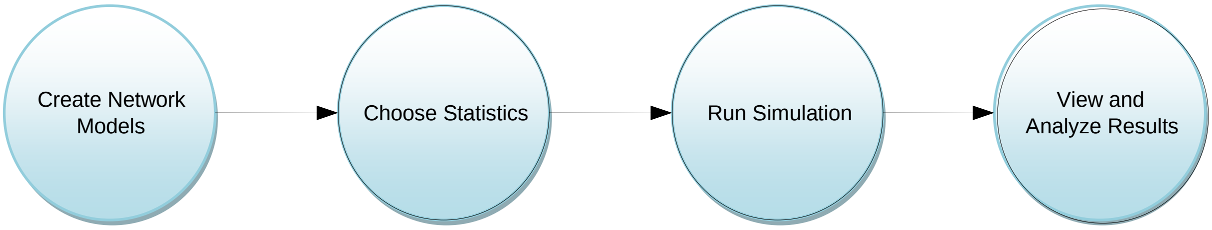
The OPNET is a very powerful network simulator. Main purposes are to optimize cost, performance and availability. The goal of this laboratory is to learn the basics of how to use Modeler interface, as well
as some basic modeling theory. The following tasks are considered:

i. Build and analyze models.
ii. Configure the object palette with the needed models.
iii. Set up application and profile configurations.
iv. Model a LAN as a single node.
v. Specify background utilization that changes over a time on a link.
vi. Simulate multiple scenarios simultaneously.
vii. Apply filter to graphs of results and analyze the results.

Before starting working on the Exercise part of this laboratory, one has to read the Preparations part.

- **Preparations**

To build a network model the workflow centers on the Project Editor. This is used to create network models, collect statistics directly from each network object or from the network as a hole, execute a simulation and view results.



- **Project Editor**

The main staging area for creating a network simulation is the Project Editor. This is used to create a network model using models from the standard library, collect statistics about the network, run the simulation and view the results. Using specialized editors accessible from the Project Editor via *File* → *New* one can create node and process models, build packet formats and create filters and parameters.

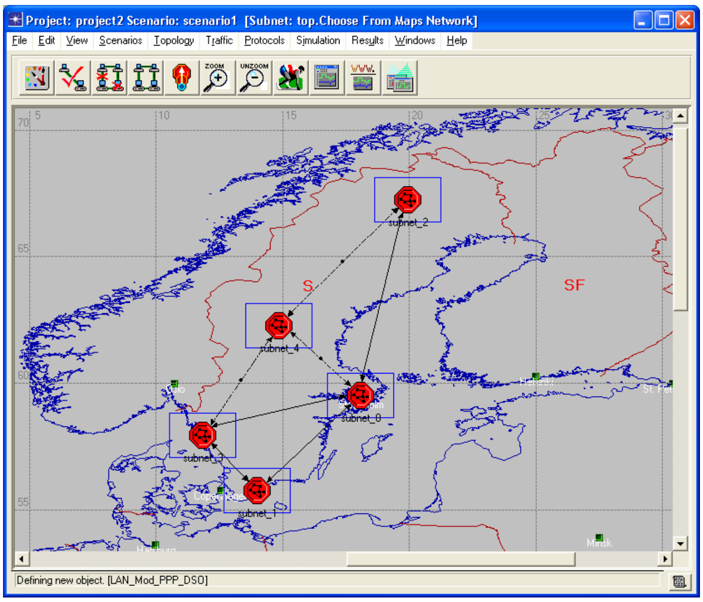


Figure 47: A network model built in project editor

- **The Node Editor**

The Node Editor is used to create models of nodes. The node models are then used to create node instances within networks in the Project Editor. Internally, OPNET node models have a modular structure. You define a node by connecting various modules with packet streams and statistic wires. The connections between modules allow packets and status information to be exchanged between modules. Each module placed in a node serves a specific purpose, such as generating packets, queuing packets, processing packets, or transmitting and receiving packets.

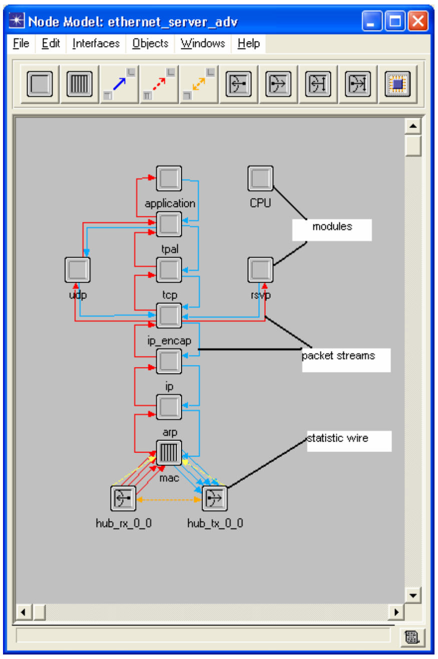


Figure 48: Node editor

- **The Process Model Editor**

To create process models which control the underlying functionality of the node models created in the Node Editor one can use the Process Editor. Process models are represented by finite state machines (FSMs) and are created with icons that represent states and lines that represent transitions between states. Operations performed in each state or for a transition are described in embedded C or C++ code blocks

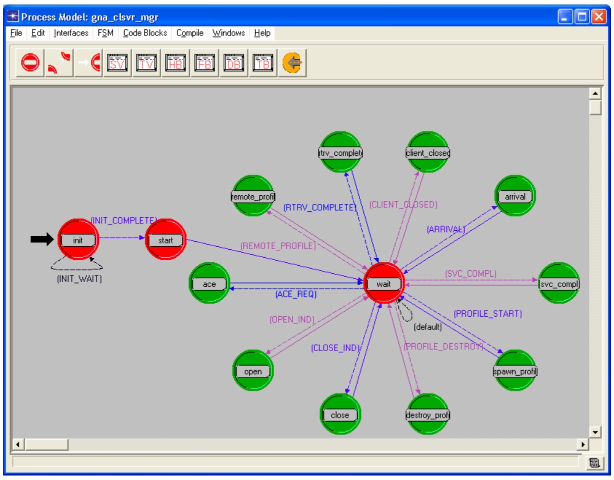


Figure 49: Process model editor

- **The Link Model Editor**

This editor enables for the possibility to create new types of link objects. Each new type of link can have different attribute interfaces and representation. Specific comments and keywords for easy recognition are also possible.

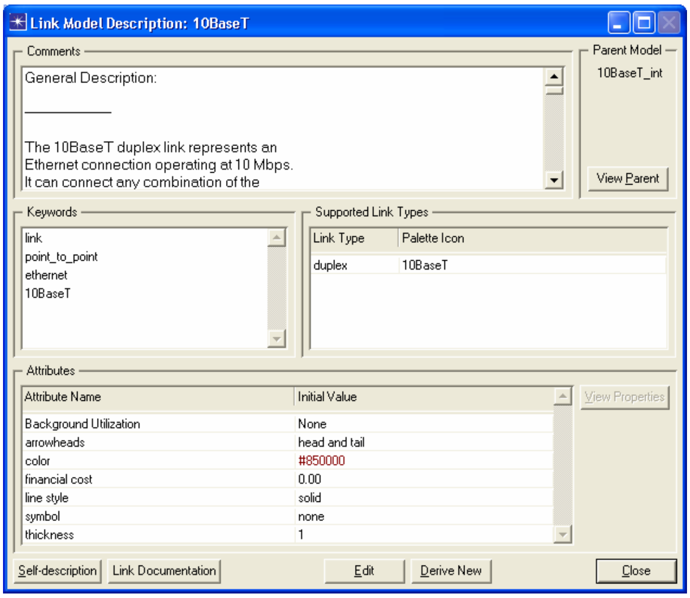


Figure 50: Link model editor

- **The Path Editor**

The Path Editor is used to create new path objects that define a traffic route. Any protocol model that uses logical connections or virtual circuits such as MPLS, ATM, Frame Relay, etc can use paths to route traffic.

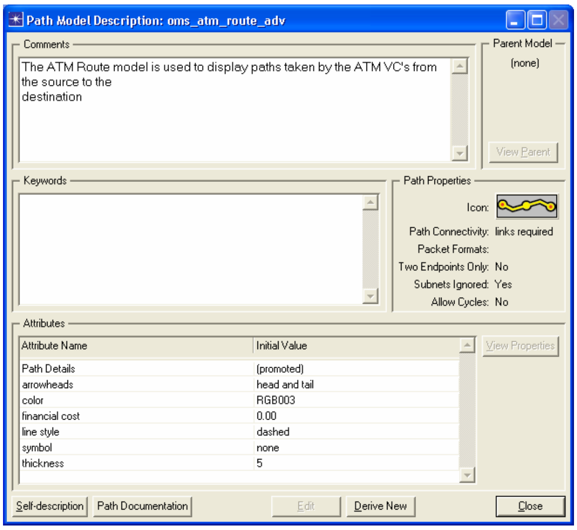


Figure 51: Path editor

- **The Packet Format Editor**

By making use of this editor it is possible to define the internal structure of a packet as a set of fields. A packet format contains one or more fields, represented in the editor as colored rectangular boxes. The size of the box is proportional to the number of bits specified as the field's size.

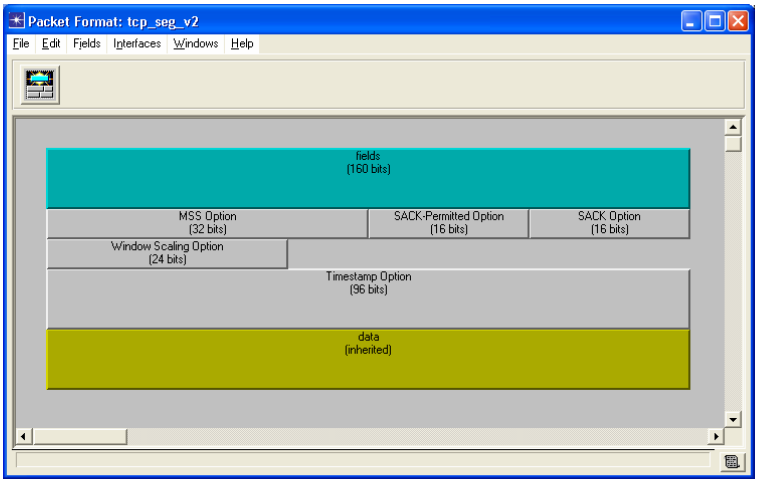


Figure 52: Packet editor

- **The Probe Editor**

This editor is used to specify the statistics to be collected. By using different probes there are several different types of statistics that can be collected, including global statistics, link statistics, node statistics, attribute statistics, and several types of animation statistics. It is mentioned that similar possibilities for collecting statistics are also available under the Project Editor. These are however not as powerful as the Probe Editor.

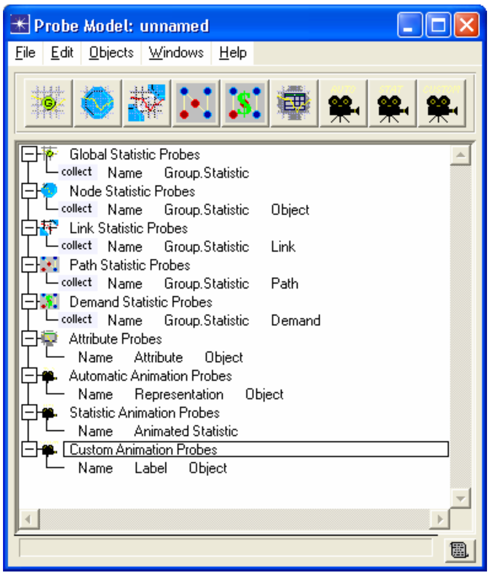


Figure 53: Probe editor

- **The Simulation Sequence Editor**

In the Simulation Sequence Editor additional simulation constrains can be specified. Simulation sequences are represented by simulation icons, which contain a set of attributes that control the simulation's run-time characteristics.

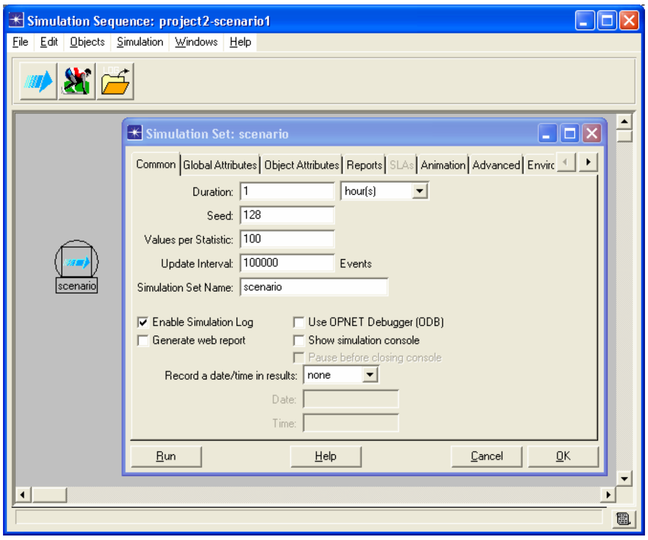


Figure 54: Simulation sequence editor

- **The Analysis Tool**

The Analysis Tool has several useful additional features like for instance one can create scalar graphics for parametric studies, define templates for statistical data, create analysis configurations to save and view later, etc.

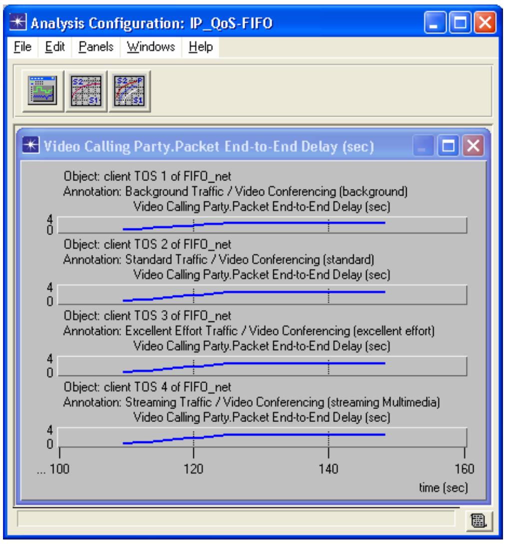


Figure 55: Analysis tool

- **The Project Editor Workspace**

There are several areas in the Project Editor window (a.k.a. workspace) that are important for building an executing a model. See Figure 11 as an example.

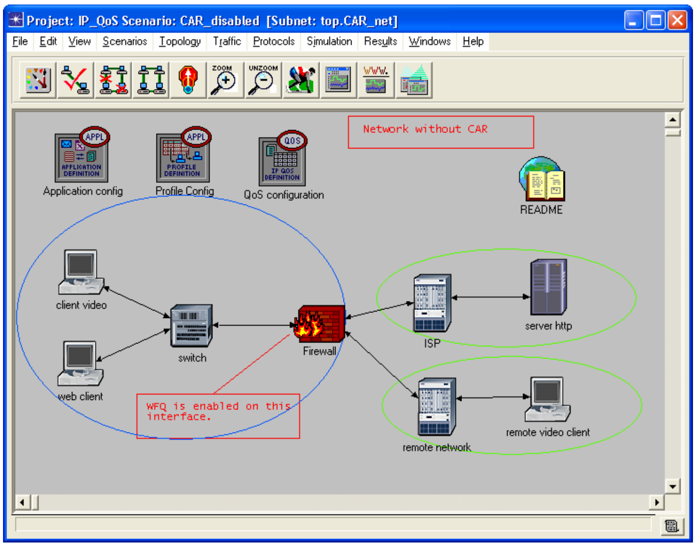
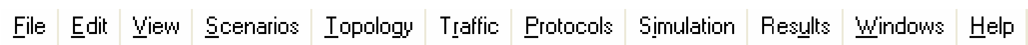


Figure 56: Project editor workspace

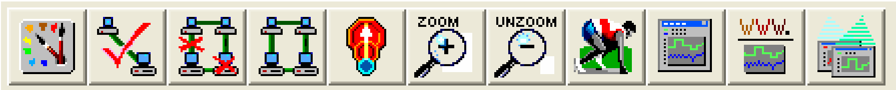
- **The Menu bar**

Each editor has its own menu bar. The menu bar shown below appears in the project editor.



- **Buttons**

Several of the more commonly used menu bar can also be activated through buttons. Each editor has its own set of buttons. The buttons shown below appear in the Project Editor.



1. Open object palette
2. Check link consistency
3. Fail selected objects
4. Recover selected object
5. Return to parent subnet
6. Zoom in
7. Zoom out
8. Configure discrete event simulation
9. View simulation results
10. View web-based reports
11. Hide or show all graphs

Appendix B

About Hexagon:

Hexagon is an engineering firm that specializes in various aspects of wireless systems: radio propagation, coverage optimization, network planning, and deployment and operation support tools. Hexagon's main product is NIR; a world-leading network planning tool integrating sophisticated propagation models and cutting edge optimization techniques. Our clients can be found all over the world, among them major telecommunication firms like AT&T, Lucent, Nera, Alvarion and Cellcom. Hexagon has an extensive ‘hands on” experience in planning, deployment and follow-up of fixed wireless networks throughout the world. Hexagon personnel published over 50 academic papers covering various aspects of network planning, propagation models and telecommunication traffic. Hexagon is actively contributing to ETSI and IEEE 802.16 standardization bodies.

Core capabilities:

Hexagon’s wireless planning tool is commercially operational since 1998 and is currently used by network operators and vendors. Capabilities implemented in the NIR that distinguish it and put it ahead of the competition are:

Radio propagation expertise

The NIR supports a variety of widely used propagation models including Knife Edge, Hata, Cost 231, ITU-R P. 530 & P.452, IEEE MMDS (SUI) and Ray Tracing. In addition Hexagon developed, implemented and tested proprietary computationally efficient propagation models that proved to provide 35% improved accuracy.

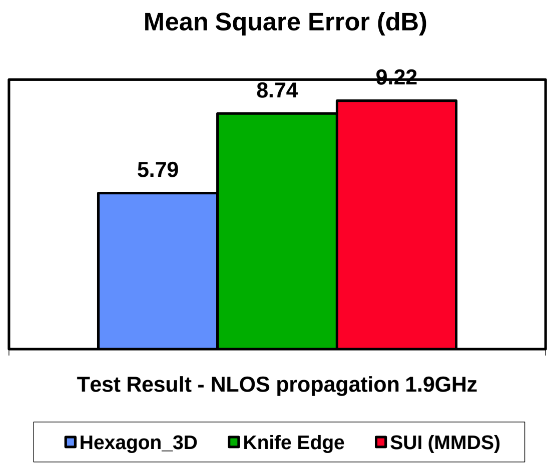


Figure 57: Mean Square Error (dB)

Coverage optimization

Hexagon has developed the ***OptiSite***, a novel algorithm to design wireless networks. Based on the input data (Geographical data, demand map, existing hubs, and potential location of additional hubs), the algorithm provides:

- Optimal site/hubs locations for a given required coverage.
- Estimation of the backbone cost sensitivity to required coverage.
- Strategic location (hubs with high marginal coverage that are difficult to replace).

This algorithm is extremely useful for efficient evolution of GSM networks to UMTS, and the introduction of WiMAX.

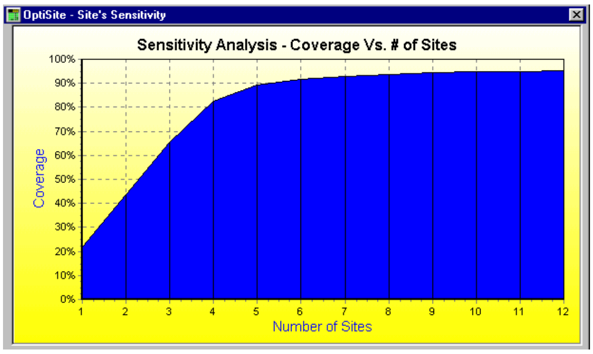


Figure 58: OptiSite

Automatic optimal frequency allocation

NIR uses a sophisticated frequency-planning algorithm, based on graph coloring techniques, that automatically allocates for each transceiver the optimal frequency of operation such that the total interference is minimized. Usage of this algorithm was proven to be remarkably more efficient and faster than common planning tools that only provide means to calculate interference map of manually allocated frequencies. The algorithm is adapted for a variety of implementations and system, including UMTS and WiMAX.

Parallel processing support

In order to cope with large databases required for high resolution analysis, the NIR supports the capability to accelerate the computation using parallel processing mechanism, based on standard PCs and Windows^{TM} network,

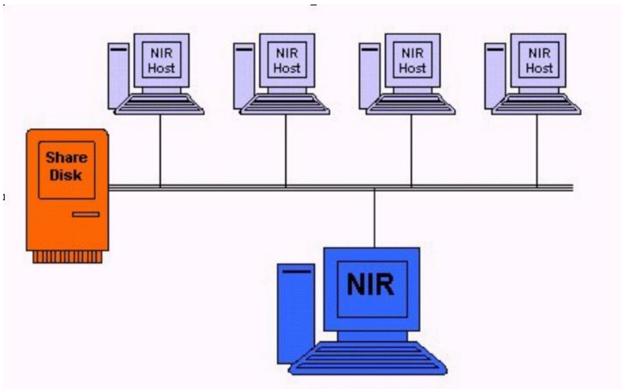


Figure 59: NIR capability

Technology combination support

The NIR supports multi-technology network planning. The network planner can define and analyze several technologies per site on a unified database. Typical applications are integrated GSM and UMTS networks or various WiMAX access networks. NIR calculates overall performance as well as possible inter-technology interference.

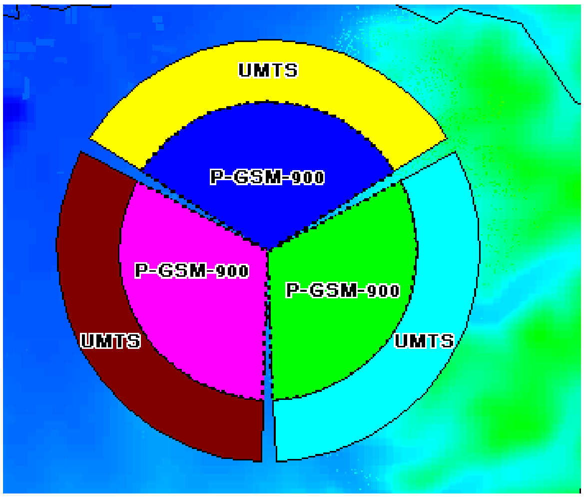


Figure 60: Network planning

NMS Integration

Hexagon provides an expert system that fuses network management data (containing the real-time behavior of the network) with the network plan (containing the RF interrelation map) to provide enhanced management tools for the wireless operator.

Drive test and Calibration analyzer

Hexagon's drive test analyzer is the operation interface of the world known PCTel's Clarify drive test equipment. In addition an advanced calibration tool was added that can provide field proven means of propagation model calibration.

Appendix C

Abbreviations and Acronyms

A

Autonomy 40

Activity agent 42

C

Call blocking probability 56

Cell splitting 18

Distributor 37, 40

Co-channel interference 15

Co-channel reuse distance 15

Cognitive radio 23

D

Delay 37, 40

DCA 28

CDCA 30

DDCA 30

F

FCA 28

Frequency reuse 14

FLCA 31

G

GSM 25

H

Handoff 25

Handoff blocking 70

HCA 30

Horizontal handoff 24

I

Intelligent software agent 41

Interference 55

M

Message complexity 37, 49

MIMO 19

N

Negotiation 40

P

Path loss 22

Power control 62

R

Reasoning 40

Resource agent 40

Resource acquisition delay 50

S

Shannon formula 74

Signal power 21

Smart antenna 19

U

UMTS 25

V

Vertical handoff 24

W

WiMAX 26

References

- Author’s Publications

[R1] Raiyn, Jamal: Using Adaptive Multimedia Mobile Agent in Heterogeneous Wireless Networks; EUROSIM2007, September 9-13, Ljubljana, Slovenia, 2007, pp. 495-501.

[R2] Raiyn, Jamal; Szczerbicka, H.: Developing Agent-Based Biological Ontology Prediction for Resource Allocation Strategy in Cellular Systems; International Symposium on Performance Evaluation of Computer and Telecommunication Systems10th Anniversary of SPECTS, July 16-18, 2007 San Diego, CA, USA, pp. 397-404.

[R3] Raiyn, Jamal: Development and Comparison between Resource Allocation Strategies based on Intelligent Scheme and Traditional Distributed Dynamic Resource Allocation Strategies in Mobile Communication Networks; Wireless Personal Communications, Volume 40, Number 4, March, 2007, pp. 495-509.

[R4] Raiyn, Jamal: A Novel Handover Scheme Based on Adaptive Agent for Reducing Real Time Communication Latency in Automation Environment; 10th International Conference on Computer Modeling and Simulation, 1-3 April, Cambridge, England, 2008, pp. 555-561.

[R5] Raiyn, J.; Freedmann, A.; Szczerbicka, H.: Using Adaptive Agent-Based Approach to Iterative Distributed Swapping Prediction for Interference Reduction in Cellular Systems; International Symposium on Performance Evaluation of Computer and Telecommunication Systems, June 16-18, Edinburgh, UK, 2008, pp. 202-208.

[R6] Raiyn, Jamal: Toward Cognitive Radio Handoff Management Based on Social Agent Technology for Spectrum Efficiency Performance Improvement of Cellular Systems; PIMRC’08, 15-18 September, Cannes France, 2008.

[R7] Raiyn, Jamal: Developing Cognitive Radio Approach Based on Dynamic SNR to reduce Handoff Latency in Cellular Systems, International Symposium on Performance Evaluation of Computer and Telecommunication Systems, July 13-16, Istanbul, Turkey, 2009, pp. 231-237

- **Other relevant publications**

[1] Agelet, F.A.; Varela, A.M.M.; Vazquez, L.J.A.; Hernando, J.M.: Optimization Methods for Optimal Transmitter Locations in a Mobile Wireless System; IEEE Transactions on Vehicular Technology Vol. 51, No. 6, November 2002, pp. 1316-1321.

[2] Akaiwa, Y.: Introduction to Digital Mobile Communication; John Wiley & Sons, INC. New York 1997.

[3] Akyildiz, I.F.; Won-Yeol, L.; Vuran, M.C.; Mohanty, S.: "A Survey on Spectrum Management in Cognitive Radio Networks,"*IEEE Communications Magazine*, Vol. 46, Issue 4, Apr. 2008. pp. 40-48.

[4] Anand, S.; Sridharan, A.; Sivarajan, K.N.: Performance Analysis of Channelized Cellular Systems with Dynamic Channel Allocation; IEEE Transactions on Vehicular Technology, Vol. 52, No. 4, July 2003, pp. 847-859.

[5] Andrade, A.; Convarrubias, D.: Radio Channel Spatial Propagation Model for Mobile 3G in Smart Antenna Systems; IEICE Trans. Commun., Vol. E86-B, No.1, January, 2003, pp. 213-220.

[6] Anton, M.D.; Kunz, D.; Rueber, B.: Channel assignment for cellular radio using simulated annealing; IEEE Transactions on Vehicular Technology, Vol. 42, No. 1, 1993, pp. 14-21.

[7] Antoniou, G.: A tutorial on default reasoning; The Knowledge Engineering Review, Vol. 13:3, 1998, pp. 225-246.

[8] Antsaklis, P.: Defining Intelligent Control; IEEE Control Systems, Vol. 14, No. 3, June 1999, pp. 58-66.

[9] Arslan, H.: Cognitive Radio, Software Defined Radio, and Adaptive Wireless Systems; Springer, Netherlands, 2007.

[10] Azad, S.; Sankar, R.: Performance of Channel Assignment Strategies in Cellular Systems; Proceedings IEEE southeastcon'99, March 1999, pp. 299-304.

[11] Baiocchi, A.; Priscoli, F.D.; Grilli, F.; Sestini, F.: The Geometric Dynamic Channel Allocation as a practical Strategy in Mobile Networks with Bursty User Mobility; IEEE Transactions on Vehicular Technology, Vol. 44, No. 1, 1995, pp.14-23.

[12] Beckmann, D.; Killat, U.: A new strategy for the application of genetic algorithms to channel assignment problem; IEEE Transactions on Vehicular Technology, Vol. 48, No. 4, 1999, pp. 1261-1269.

[13] Bergounioux, M.; Kunisch, K.: On the structure of Lagrange multipliers for state-constrained optimal control problems; Optimization and Control of Distributed Systems, volume 48, issues 3-4, March 2003, pp. 169-176.

[14] Bertoni, L.H.: Radio Propagation for Modern Wireless systems; Prentice Hall PTR, New Jersey, 2000.

[15] Blaunstein, N.: Prediction of cellular characteristics for various urban environments; IEEE Antennas Propagation Magazine, Vol. 41, No. 6, 1999, pp. 135-145.

[16] Blaunstein, N.: Radio Propagation in Cellular Networks; Artech House, London 2000.

[17] Blaunstein, N.: Christodoulou, C.G.: Radio Propagation and Adaptive Antennas for Wireless communication Links; Wiley, USA, 2007.

[18] Bodanese, E.L.; Cuthbert, L.G.: Application of intelligent agents in channel allocation strategies for mobile networks; IEEE International conference on communications, Vol. 1, June 18-22, 2000, pp. 181-185.

[19] Box, F.: A heuristic technique for assigning frequencies to radio nets; IEEE Transactions on Vehicular Technology, Vol. 27, No. 2, 1978, pp. 57-64.

[20] Breyer, S.; Dega, G.; Kumar, V.; Szabo, L.: Eine globale Ansicht des UMTS-Konzept; Alcatel Telecom, Rundschau 1999.

[21] Bublin, M.; Konegger, M.; Slanina, P.: A Cost-Function-Based Dynamic Channel Allocation and Its Limits; IEEE Transactions on Vehicular Technology, Vol. 56, No. 4, July 2007, pp. 2286-2295.

[22] Cao, G.: Integration Distributed Channel Allocation and Adaptive Handoff Management for QoS-Sensitive Cellular Networks; Wireless Networks 9, 2003, pp. 1984-1987.

[23] Capone, A.; Trubian, M.: Channel Assignment Problem in Cellular Systems: a new Model and a Tabu Search Algorithm; IEEE Transaction on Vehicular Technology, 1999, pp. 1252-1260.

[24] Castro, J.: Software Engineering for Large-Scale Multi-Agent Systems; Springer-Verlag Berlin 2003.

[25] Chan, P.T.H.; Palaniswami, M.; Everitt, D.: Neural network-based dynamic channel assignment for cellular mobile communication systems; IEEE Transactions on Vehicular Technology, Vol. 43, No. 2, 1994, pp. 279-188.

[26] Chen, J.; Tan, W.K.: Predictive Dynamic Channel Allocation Scheme for Improving Power Saving and Mobility in BWA Networks; Mobile Network Application, 2007, pp. 197-201.

[27] Chen, K.G.: Effects of Sectorization on Spectrum Efficiency of Cellular Systems; IEEE Transaction on Vehicular Technology, Vol. 41, No. 3, August 1992, pp. 217-225.

[28] Cheng, K.C.: Introduction to Mobile WiMAX; NTUEE Mobile Communication, 2007.

[29] Chih, I.L.: Distributed Dynamic Channel Allocation Algorithms with Adjacent Channel Constraints; PIMRC, 2004, pp. 787-791.

[30] Chong, P.H.J.; Leung, C.: A new Channel Borrowing Scheme with Interference Information for Cellular Systems; IEEE 49th Vehicular Technology Conference, Texas, May, USA, 1999, pp. 20-24.

[31] Cimini, L.G.; Foschini, G.J.: Distributed Dynamic Channel Allocation Algorithms for Microcellular Systems, Wireless Communications, Future Directions; Kluwer Academic Publishers, Boston, London, 1993.

[32] Clearwater, S.H.: Market-Based Control: A Paradigm for Distributed Resource Allocation; World Scientific, New Jersey 1996.

[33] "Cognitive Radio Definition"; Virginia Tech Cognitive Radio Work Group Wiki. AvailableOnline: http://support.mprg.org/dokuwiki/doku.php?id=cognitive_radio:definition.

[34] Comments of the National Telecommunications and Information Administration on FCC ET Docket No. 03-108: "Facilitating Opportunities for Flexible, Efficient, And Reliable Spectrum Use Employing Cognitive Radio Technologies"; February 15, 2005.

[35] Cong, L.; Gunawan, E.: Performance analysis of dynamic channel assignment algorithms in cellular mobile systems with hand-off; International Journal of Communication Systems, 2002, pp. 683-700.

[36] Cruz-Perez, F.A.; Rodriguez, D.L.: DDCA with VRP: a New Family of Distributed Dynamic Channel Assignment Algorithms for Microcellular Systems; 48th IEEE Vehicular Technology Conference, Ottawa, Canada, May 1998, pp. 11-15.

[37] Cruz-Perez, F.A.; Lara-Roderiguez, D.: Distributed Dynamic Channel Assignment with Violation to the Reuse Pattern for Microcellular Networks; IEEE Transactions on Vehicular Technology, Vol. 51, November 2002, pp. 1375-1385.

[38] Dalmeijer, M.; Hammer, D.J.; Aerts, A.T.M: Mobile software agents; Computers in Industry, Vol. 41, No. 3, May 2000, pp. 251-260.

[39] David, K.; Benkner, T.: Digitale Mobilfunksysteme; B.G. Teubner Stuttgart, 1996.

[40] Do, M.-S.; Park, Y.; Lee, J.Y.: Channel Assignment with QoS Guarantees for a Multiclass Multicode CDMA System; IEEE Transactions on Vehicular technology, Vol. 51, September 2002, pp. 935-948.

[41] Dong, X.; Lai, T.H.: Distributed dynamic carrier allocation in mobile cellular networks: Search vs. update; Proceedings of the 17th International Conference on Distributed Computer Systems, Baltimore, Maryland, May 1997, pp. 108-115.

[42] Dong, X.; Lai, T.H.: An efficient priority-based dynamic channel allocation for mobile cellular networks; IEEE INFOCOM 1997, pp. 892-899.

[43] Draft Document: Standard Definitions and Concepts for Spectrum Management and Advanced Radio System Technologies, June 2, 2006.

[44] Dramitinos, M.; Stamoulis, G.D.; Courcoubetis, C.: Auction-Based Resource Reservation in 2.5/3G networks; Mobile Networks and Applications 9, 2004, pp. 557-566.

[45] Eaves, J.L.; Reely, E.K.: Principles of Modern Radar; Van Nostrand Reinhold Company, New York 1987.

[46] Ekiz, N.; Salih, S.; Kucukoner, S.; Fidanboylu, K.: An Overview of Handoff Techniques in Cellular Networks; International Journal of Technology, Vol. 2, No. 1, 2005, pp. 343-347.

[47] El-Osery, A.; Abdallah, C.: Distributed Power control in CDMA Cellular systems; IEEE Antennas and Propagation Magazine, Vol. 42, No. 4, August 2000, pp. 152-159.

[48] ET Docket No. 03-108, March 11, 2005.

[49] Evci, C.; Barth, U.; Sehier, P.: Strategic and Technological Challenges for Wireless Communications beyond 3G; Journal of Communications and Networks, Vol. 4, No. 4, December 2002, pp. 717-722.

[50] Ferng, H.W.; Tsai, Y.C.: Using Priority, Buffering, Threshold Control, and Reservation Techniques to Improve Channel-Allocation Schemes for the GPRS System; IEEE Transactions on Vehicular Technology, Vol. 54, No. 1, January 2005, pp. 89-92.

[51] Foschini, G.J.; Miljanic, Z.: A simple distribute autonomous power control algorithm and its convergence; IEEE Transactions on Vehicular Technology, Vol. 42, No. 4, Nov. 1993, pp. 641-646.

[52] Foschini, G.J.; Miljanic, Z.: Distributed autonomous wireless channel assignment algorithm with power control; IEEE Transactions on Vehicular Technology, Vol. 44, No. 3, August 1995, pp. 420-429.

[53] Friedlander, B.; Scherzer, S.: Beamforming Versus Transmit Diversity in the Downlink of a Cellular Communications System; IEEE Transactions on Vehicular Technology, Vol. 53, No. 6, November 2004, pp. 1023-1034.

[54] Funabiki, N.; Takefuji, Y.: A neutral network parallel algorithm for channel assignment in cellular radio networks; IEEE Transactions on Vehicular Technology, Vol. 41, No. 4, 1992, pp. 430-437.

[55] Gamst, A.: Some lower bounds for a class of frequency assignment problems; IEEE Transactions on Vehicular Technology, Vol. 35, No. 1, 1986, pp. 8-14.

[56] Garg, V.K.: Wireless Communications and Networking; Morgan Kaufmann Publishers, Amsterdam, 2007.

[57] Garg, V.K.; Wilkes, E. J.: Principles and Applications of GSM; Prentice Hall PTR, London 1999.

[58] Grandhi, S.A.; Zander, J.; Yates, R.: Constrained power control; Wireless Personal Communications, Vol. 1, No.4, 1995, pp. 257-270.

[59] Gupta, M.; Sachan, A.K.: Distributed Dynamic Channel Allocation Algorithm for Cellular Mobile Network; Journal of Theoretical and Applied Information Technology, Vol. 3, No. 3, 2007, pp. 58-63.

[60] Gupta, S.; Srimani, P.: Distributed Dynamic Channel Allocation in Mobile Networks: combining Search and Update; The Journal Supercomputing Vol.17, No.1, August 2000, pp. 1-15.

[61] Gwon, Y.; Jain, J.; Kawahara, T.: Robust Indoor Location Estimation of Stationary and Mobile Users; IEEE INFOCOM, 2004, pp. 1032-1043.

[62] Hamidian, K.; Payne, J.: Performance Analysis of a CDMA/FDMA Cellular Communication System with Cell Splitting; 2nd IEEE Symposium on Computer and Communications, 1997, pp. 545-551.

[63] Harroud, H.; Karmouch, A.: AGENT-BASED NEGOTIATION FOR MOBILE USERS; QoS Management in wired & wireless Multimedia Communication Networks, Vol.2, No.2-4, January 2000.

[64] Hartroth, J.; Kottmann, D.: Mobile Softwareagenten: Entwicklungsstand und Einsatzperspektiven; Theorie und Praxis der Wirtschaftsinformatik, heft 190, Juli, 1996, Huethig.

[65] Hashemi, H.: The indoor radio propagation channel; Proc. IEEE, Vol. 81, No. 7, 1993, pp. 943-968.

[66] Haykin, S.: Cognitive Radio: Brain-Empowered Wireless Communications; IEEE Journal on Selected Areas in Communications, Vol. 23, No 2, Feb. 2005, pp. 201-220.

[67] Hayzelden, A.L.G.; Bigham, J.: Agent technology in communications systems: an overview; The Knowledge Engineering Review, Vol. 14, No. 4, United Kingdom, 1999, pp. 341-375.

[68] Helin, H.; Laamanen, H.; Raatikainen, K.: Mobile Agent Communication in Wireless Networks; ITG-Fachberichte, European Wireless, VDE Verlag Berlin 1999.

[69] Herscovici, N.; Christodoulou, C.: Smart-Antenna Systems for mobile Communication Networks; IEEE Antenna's and Propagation Magazine, Vol. 44, No.3, June 2002, pp. 1461-1475.

[70] Herscovici, N.; Christodoulou, C.: On the Eigenvalue Distribution of Smart-Antenna Arrays in Wireless Communication Systems; IEEE Antennas and Propagation Magazine, Vol. 46, No. 4, August 2004, pp. 158-173.

[71] Hong, D.; Rappaport, S.S.: Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and non prioritized handoff

procedures; IEEE Transactions Vehicular Technology, Vol. VT-35, No. 3, August 1986, pp. 77-92.

[72] Honkasalo, Z.C.; Steffen, J.L.; Holma, H.; Wacker, A.; Sipilae, K.; Haemaelaeinen, S.: Radio Network Planning; John Wiley, 2001.

[73] Huhns, M.N.; Singh, M.P.: Readings in Agents; Morgan Kaufmann Publishers, USA 1998.

[74] Hung, P.; Wolf, A.S.; Sycara, K.: DESIGN OF A MULTI-UNIT DOUBLE AUCTION E-MARKET; Computational Intelligence, Vol. 18, No. 4, 2002, pp. 596-617.

[75] Hurley, S.: Planning Effective Cellular Mobile Radio Networks; IEEE Transactions on Vehicular Technology, Vol. 51, No 2, March 2002, pp. 243-296.

[76] "Improving Spectrum Usage through Cognitive Radio Technology"; IEEE USA Position,Nov,13,2003,Availableonline: http://www.ieeeusa.org/policy/positions/cognitiveradio.asp.

[77] Jain, R.: The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling; John Wiley & Sons, 1991.

[78] Javidi, T.: Decentralized Rate Assignment in a Multi-sector CDMA Network; GLOBCOM 2003.

[79] Jun, Y.; Cheng, S.: A new Dynamic Channel Assignment Strategy in Cellular Mobile Communication Systems; IEEE International Conference on Communications, Vol. 3&4, 1992, pp. 1312-1315.

[80] Jung, B.C.; Hong, Y.J.; Sung, D.K.; Chung, S.Y: Fixed Power Allocation with Nulling for TDD-Based Cellular Uplink; IEEE Communications Letters, Vol. 12, No. 4, April 2008.

[81] Katzela, I.; Naghshineh, M.: Channel Assignment Schemes for Cellular Mobile Telecommunication Systems; IEEE Personal Communications, Vol.3, No.3, June 1996, pp. 10-31.

[82] Kim, J.S.; Park, S.H.; Dowd, P.W.; Nasrabadi, N.M.: Cellular radio channel assignment using a modified Hopfield network; IEEE Transactions on Vehicular Technology, Vol. 46, No. 4, 1997, pp. 957-967.

[83] Kim, S.W.; Kim, B.-S.; Fang, Y.: Downlink and Uplink Resource Allocation in IEEE 802.11 Wireless LANs; IEEE Transactions on Vehicular Technology, Vol. 54, No. 1, January 2005, pp. 320-327.

[84] Kumilo, F.: Wireless Digital Communications, Modulation & Spread Spectrum Applications; Prentice-Hall PTR 1995.

[85] Kunz, D.: Channel assignment for cellular radio using neural networks; IEEE Transactions on Vehicular Technology, Vol. 40, No. 1, 1991, pp. 188-193.

[86] Labrou, Y.; Fini, T.; Peng, Y.: Agent Communication Languages: The Current Landscape; IEEE Intelligent Agent Systems, Vol. 14, No. 2, March/April 1999, pp. 45-52.

[87] Lai, W.K.; Coghill, G.G.: Channel assignment through evolutionary optimization; IEEE Transactions on Vehicular Technology, Vol. 45, No. 1, 1996, pp. 91-96.

[88] Lee, T.; Hwang, S.C.: An Efficient Distributed Channel Allocation Scheme Through Statistical Analysis in Cellular Networks; Proceedings of the Seventeenth IASTED International Conference Applied Informatics, February, 1999, Austria, pp. 558-561.

[89] Lee, W.C.Y.: Mobile Communications Design Fundamentals; John Wiley and Sons, 1993.

[90] Lee, W.C.Y: Mobile Cellular Telecommunications: Analog and Digital Systems; Second Edition, McGraw-Hill 1995.

[91] Lee, Y.C.W.: Spectrum Efficiency and Digital Cellular; 38th IEEE Vehicular Technology Conference, Philadelphia, June 1998.

[92] Lehne, P.H.; Pettersen, M.: An Overview of smart antenna technology for mobile communications systems; IEEE Communication Surveys, Fourth Quarter 1999, Vol. 2 No.4, 1999, pp. 3-29.

[93] Li, C.; Che, H.; Li, S.: A Wireless Channel Capacity Model for Quality of Service; IEEE Transactions on Wireless Communications, Vol. 6, No. 1, January 2007, pp. 357-366.

[94] Li, J.; Farahvash, S,; Kavehrad, M.; Valenzuela, R.: Dynamic TDD Fixed Cellular Systems Using Smart and Sectored Antennas; International Journal of Wireless Information Networks, Vol. 9, No. 4, October 2002, pp. 1627-1636.

[95] Li, J.; Shroff, N.B.; Chong, E.K.P.: Channel Carrying: A Novel Handoff Scheme for Mobile Cellular Networks; INFOCOM '97, pp. 908.

[96] Li, X.; Wu, D.: Power control and channel allocation for real-time applications in cellular networks; Wireless Communications and Mobile Computing, Vol. 8, No. 6, 2007, pp. 705-713.

[97] Lin, Y.-B.; Chlamtac, I.: Wireless and Mobile Network Architectures; John Wiley & Sons, New York 2001.

[98] Lin, P.: Channel Allocation for GPRS with Buffering Mechanism; Wireless Networks 9, 2003, pp. 431-441.

[99] Luck, M.; Marik, V.; Stepankova, O.; Trappl, R.: Multi-Agent Systems and Applications; Springer 2001.

[100] Mac Donald, V.H.: Advanced Mobile Phone Service: The Cellular Concept; The Bell System Technical Journal, Vol. 58, No. 1, January 1979, pp. 15-41.

[101] Mason, P.C.; Cullen, J.M.; Lobley, N.C.: UMTS Architectures; The Institute of Electrical Engineerings, IEEE 1996.

[102] Mehrotra, A.: Cellular Radio Analog and Digital System; Boston, Artech House, 1994.

[103] Misic, J.; Tam, Y.B.: Non- Uniform Traffic Issues in DCA Wireless Multimedia Networks; Wireless Networks 9, 2003, pp. 2730-2736.

[104] Mitola, J.: Cognitive Radio for Flexible Multimedia Communications; Mobile Multimedia Communications, 1999. (MoMuC '99) IEEE International Workshop 1999, pp. 3 –10.

[105] Mitts, H.: Use of Intelligent networks in the UMTS; Intelligent Software-Agenten in elektronischen Märkten, 1996.

[106] Naik, K.; Wei, D.S.L.: Call-on-Hold for Improving the Performance of Dynamic Channel-Assignment Strategies in Cellular Networks; IEEE Transactions on Vehicular Technology, Vol. 53, No. 6, November 2004, pp. 15-41.

[107] Nesargi, S.; Prakash, R.: Distributed Wireless Channel Allocation in Networks with Mobile Base Stations; Proceedings of INFOCOM 1999, pp. 592-600.

[108] Ngo, C.Y.; Li, V.O.K.: Fixed channel assignment in cellular radio networks using a modified genetic algorithm; IEEE Transactions on Vehicular Technology, Vol. 47, No.1, 1998, pp. 163-172.

[109] Nwana, H.S.; Ndumu, D.T.: An introduction to agent technology; BT Technology Journal, Vol. 14, No 4, 1996, pp. 55-67.

[110] Okada, K.; Kubota, F.: On Dynamic Channel Assignment in Cellular Mobile Radio Systems; IEEE International Symposium 1991.

[111] http://www.opnet.com.

[112] Pahlavan, K.; Levesque, A.: Wireless Data Communications; Proc. of IEEE, Vol. 82, No. 9, September 1994, pp. 23-41.

[113] Park, D.-K.; Okada, K.; Yoshimoto, S.: Performance of Distributed Dynamic Channel Assignment in Cellular Systems; Journal of the Communications Research Laboratory, No. 3, Nov. 1995, Japan, pp. 1855-1859.

[114] Pechovcek, M.: Multi-agent systems and applications 3; 3rd International Central and Eastern European Conference on Multi-Agent Systems, Springer, Berlin 2003.

[115] Prakash, R.; Singhal, M.; Shivaratri, N.G.: Distributed Dynamic Channel Allocation for Mobile Computing; Proceedings of the Fourteenth Annual ACM Symposium on Principles of Distributed Computing, Ottawa 20-23, 1995, pp. 47-56.

[116] Prasad, R.: Universal Wireless Personal Communication; Artech House, London, 1998.

[117] Rappaport, S.S.: Blocking, hand-off and traffic performance for cellular communication systems with mixed platforms; Proc. IEE, Vol. 140, Oct. 1993, pp. 389–401.

[118] Re, D.L.; Fantacci, R.; Giambene, G.: Call Blocking Performance for Dynamic Channel Allocation Technique in Mobile Satellite Systems; IEE Proc. Commun., Vol 143, No.5, October, 1996, pp. 289-296.

[119] Redl, A. S.; Weber, K. M.; Oliphant, W. M.: An Introduction to GSM; Artech House Publishers, London 1995.

[120] Reinhold, E.; Walter, F.: Mobilfunknetze; Vieweg, Braunschweig 1993.

[121] Roy, S.D.: A Timer Based Handoff Algorithm for Multi-Cellular Systems; ICETET, 2008 First International Conference on Emerging Trends in Engineering and Technology 2008, pp. 819-822.

[122] Sarkar, S.; Sivarajan, K.N.: Channel Assignment Algorithms Satisfying Cochannel and Adjacent Channel Reuse Constraints in cellular Mobile Networks; IEEE Transactions on Vehicular Technology, Vol. 51, No. 5, September 2002, pp. 954-967.

[123] Scheibenbogen, M.; Clausen, S.; Guntsch, A.: Dynamical Channel Allocation in Hierachical Cellular Systems, IEEE Pacific RIM Conference; Vol. 1, Victoria, Canada 1997, pp. 65-71.

[124] Shimada, K. M.; Abe, T.: A Flexible Hybrid Channel Assignment Strategy Using an Artificial Neural Network in a Cellular Mobile Communication System; IEICE Transactions on Fundamentals of Electronics, Communications and Computer Science, Vol. E78-A, No. 6, June 1995, pp. 693-700.

[125] Schubert, M.; Boche, H.: Solution of the Multiuser Downlink Beamforming Problem with Individual SINR Constraints; IEEE Transaction Vehicular Technology, Vol. 53, January 2004, pp. 18-28.

[126] Schwartz, M.: Mobile Wireless Communications; Cambridge University Press, 2007.

[127] Seth, A.; Gupta, H.M.; Momaya, K.: Quality of service parameters in cellular mobile communication; International Journal of Mobile Communications, Vol. 5, No. 1, 2007, pp.65-93.

[128] Sim, K.M.: A MARKET-DRIVEN MODEL FOR DESIGNING NEGOTIATION AGENTS; Computational Intelligence, Volume 18, number 4, 2002, pp. 643-662.

[129] Spencer, H. Q.; Peel, B. C.; Swindlehurst, L.A.; Haardt, M.: Introduction to the Multi-User MIMO Downlink; IEEE Communications Magazine, October 2004, pp. 60-62.

[130] Springer, T.; Ziegert, T.; Schill, A.: Mobile Agents as an Enabling Technology for Mobile Computing Applications; Künstliche Intelligenz, Heft 4, Oktober, 2000, pp. 284-289.

[131] Stankovic, V.; Hamzaoui, R.; Xiong, X.: Efficient Channel Code Rate Selection Algorithms for Forward Error Correction of Packetized Multimedia Bitstreams in Varying Channels; IEEE Transactions on Multimedia, Vol. 6, No. 2, April 2004, pp. 91-107.

[132] Steven, L.C.; Peter, H.J.C.: Capacity improvement with dynamic channel assignment and reuse partitioning in cellular systems; Journal of communication and networks, Vol. 8, No. 1, 2006, pp. 13-20.

[133] Tandai, T.; Horiguchi, T.; Deguchi, N.; Tomizawa, T.; Tomioka, T.: A Study on Cognitive Radio Coexisting with Cellular Systems; IEICE Trans. Comm. Vol. E91-B, No. 1, January 2008, pp. 38-52.

[134] Tejaskumar, P.; Anvekar, D.K.; Sonde, B.S.: DCBWL: A new channel Borrowing Scheme for Mobile Cellular Communication Systems; Proceedings of the 1996 IEEE International Conferences on Personal Wireless Communications, New Delhi, India, February 1996, pp.162-167.

[135] Tekinay, S.; Jabbari, B.: Handoff and channel assignments in mobile cellular networks; IEEE Communications Magazine 29(11), 1991, pp. 42–46.

[136] Thanh, D.J.; Steensen, S.; Audestand, J.A.: Mobility Management and Roaming with Mobile Agents; International Workshop, MWCN 2000, Paris, May 2000, pp. 123-137.

[137] Tisal, J.: GSM Cellular Radio Telephony; John Wiley & Sons, New York, 1997.

[138] Tse, D.; Viswanath, P.: Fundamental of Wireless Communication; Cambridge University Press, 2005.

[139] Vannithamby, R.; Sousa, E.S.: A Channel Allocation Scheme for both Uniform and Non-Uniform Traffic Environment in Cellular Networks; 12th International Symposium on Personal, Indoor and Mobile Radio Communications, California USA, 2001.

[140] Voos, H.; Litz, L.: A NEW APPROACH FOR OPTIMAL CONTROL USING MARKET-BASED ALGORITHMS; Proceedings of the European Control Conference ECC 1999.

[141] Voos, H.: Market-based control of complex dynamic systems; IEEE International Symposium on Intelligence Control, Cambridge, Sept. 1999, pp. 808-817.

[142] Wang, J.; Zeng, Q.A.; Agrawal, D.P.: Performance Analysis of a Preemptive and Priority Reservation Handoff Scheme for Integrated Service- Based Wireless Mobile Networks; IEEE Transactions on Mobile Computing, Vol. 2, No. 1, January- March 2003, pp. 1270-1283.

[143] Wei, W.; Soong, B.H.; Tan, P.T.; Gunawan, E.; Soh, C.B.: Distributed Algorithms for Dynamic Channel Allocation in Cellular Mobile Systems; IEEE Universal Personal Communications, 1994.

[144] Wittig, H.: Intelligent Media Agents; Vieweg, Germany 1999.

[145] Yeqin, M.; Guangzeng, F.: A New Dynamic Channel Allocation Scheme for Microcellular Systems; International Conference on Communication Technology, October, China 1998, pp. 563-569.

[146] Xhafa, A.E.; Tonguz, O.K.: Handover Performance of Priority Schemes in Cellular Networks; IEEE Transactions on Vehicular Technology, Vol. 57, No. 1, January 2008, pp. 565-577.

[147] Zhang, M.; Yum, P.-S.T.: Comparisons of Channel-Assignment Strategies in Cellular Mobile Telephone Systems; IEEE Transactions on Vehicular Technology, Vol. 38, No. 4, November 1989, pp. 211-215.

[148] Zhao, S.; Xiong, Z.; Wang, X.: Optimal Resource Allocation for Wireless Video over CDMA Networks; IEEE Transaction on Mobile Computing, Vol. 4, No. 1, January/ February 2005, pp. 441-424.

[149] Xie, H.; Kuek, S.: Priority Handoff Analysis; Proc. 43rd IEEE VTC, 1993, pp. 855–58.

[150] Zysman, G.I.; Menkes, H.: Wireless Mobile Communications at the Start of the 21st Century; IEEE Communications Magazine, January 2001, pp. 110-116.

Curriculum Vitae

Jamal Raiyn received the first diplom in applied mathematics from Siegen University in Germany, in 1998, and the second diplom in mathematics and computer science from Leibniz University of Hannover in Germany, in 2000. From January 2001 to April 2002, he worked in institute for Data Communications System at the University of Siegen in Germany. From 2002 to 2004 he worked as a fellow researcher in school for electrical engineering in Tel-Aviv University in Israel. Since September 2002 till now, he is a lecturer in Computer Science Department at the Al-Qasemi Academy in Israel. In addition he is working toward PhD degree at Leibniz University of Hannover/Germany.