NOVEL TECHNIQUES FOR INTEGRATION OF SUPER-USERS IN CELLULAR NETWORKS

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CONTENTS

SUMMARY

This work proposes and analyses a method for smooth accommodation of a class of super data users within 2.5G / 3G TDMA cellular systems. It is well known that the current and coming data services for wireless mobile users are very limited, mainly due to the capacity problems. Introduction of a class of super data users is therefore very challenging. This method proposes to take advantage of the simultaneous services of a plurality of base-stations. Splitting the data stream from a plurality of servers to the mobile achieving thereby an optimal sharing of the load can greatly accommodate super-users compared to a normal system. It is shown that the almost continuous overlapping created by adjacent and umbrella cells makes this scheme possible. The design and performance of this scheme is then investigated. We conclude on the concrete applications of this concept, which are typically: demanding individual super-users (security / business) and "aggregated" super-users (mobile hot-spots in buses or trains aggregating all the passengers' needs in one pipe).

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CHAPTER I INTRODUCTION

I.1. Scope of the project

Providing decent wireless data services has become a major goal of telecommunications research and industry. Service providers are promising QoS (Quality of Service) and higher data rates for the future. It will remain that the basic offer will still be way below standard expectations: E-GPRS (Enhanced General Packet Radio Services) and WCDMA (Wideband Code Division Multiple Access) will provide concretely an offered throughput between 100 Kbps and 2 Mbps. This work is part of a wider project involving several persons aiming at exploring the possibilities of establishing a privilege restricted class of users within existing and coming wireless systems who would be offered top class wireless services. This can be aimed at demanding individuals or structurally at “aggregated” users in the network. More precisely this means seamless mobility and significantly higher data rates. The ideas which have been worked on under this project are mainly bandwidth aggregation (homogeneous and/or heterogeneous wireless systems), simultaneous usage of a plurality of wireless access point (being WLAN stations, cellular base-stations,…), and efficient resources allocation management by making use of the specificity of the environment and the mobile’s current location. The feasibility of a few very interesting concrete applications which have been thought through depends on the efficiency of the implementation of such ideas. The potential interest of simultaneous service by a plurality of base-stations (BSs) has been briefly addressed by the team for CDMA systems [1][2]. Work and experiments are undergoing within the team [3] showing the potential of a new transport protocol (Stream Control

Transmission Protocol) for heterogeneous systems bandwidth aggregation and seamless inter-systems mobility management.

This dissertation reports the results and finding of a multiple base-stations service scheme within 2.5G / 3G TDMA cellular systems.

I.2. Motivations

The challenge in the integration of a small super user class in a cellular system resides in capacity. Cellular systems reuse spatially the allocated spectrum in order to accommodate a decent number of users anywhere in the network. The space is therefore divided into cells which are served by a base-station. This base-station is allocated a number of channels for servicing its area. This allocation can be dynamic, hybrid or static. It has been shown [4]-[5] that dynamic channel assignment, though theoretically attractive, is difficult to implement, may lead to instability and performs poorly in congestion situations. This explains why, as far as TDMA/FDMA cellular systems are concerned, the allocation of channels per cell is still mostly static in pratice. Fixed channel assignment leads to a situation whereby each cell has a finite amount of resources. Some limited improvements have been made to cope with temporary high traffic within a cell, such as channel borrowing from other cells. However, the amount of resources per cell can reasonably be considered as fixed (in reality, not in research).

The introduction of data services in GSM voice systems has been made in a limited fashion through GPRS. GPRS is an efficient packet-switched system and thus can be integrated with low data rates without much harm. The arrival of EDGE (Enhanced Data Rates for GSM Evolution) will potentially triple the data-rate through a more efficient modulation scheme. GPRS and E-GPRS are bandwidth aggregation schemes in themselves. They potentially allow decent data-rates by grouping several channels. However, operators are foreseen to be reluctant to allow high class grouping since it would affect their scarce capacity. Thus, trying to introduce a super-user class (even a small one) without any modification is very dangerous since each cell has a finite amount of resources. Even if the need is there and the technology might exist, operators are not likely to allow it. Available commercial GSM benchmarks [6] give a typical number of frequencies per cell of 1 to 3, which means 8 to 24 channels. A super-user would typically need a least 10 channels (220 kbps with GPRS, 560 kbps at best with E-GPRS) if not more. The arrival of such a load in a single cell will therefore have a dreadful impact on other users (existing or coming) within the cell.

To overcome this problem we propose here to allow the super-user to be served by a plurality of BS, as illustrated in Figure A. Assuming in our example that the user can receive a good signal from 3 BS, and since the allocated channels to adjacent or over-laying cells are disjoint, the user can get 3 or 4 channels per base-station achieving thus its need. A sudden charge of 3 or 4 channels in an 8 to 24 channels cell is very bearable. This is definitely applicable in the downlink, since BS antennas are now mostly sectorized. On the contrary, this is less interesting in the uplink. This idea raises numerous challenges in term of feasibility, complexity, design and performance.

I.3. Organization of the thesis

In a first part, we present a clear picture of the concepts analyzed here. Past work on data-splitting, load-sharing and multiple base-station service will be briefly reviewed. We then focus on the feasibility at the physical layer. This method assumes that a mobile user can be covered simultaneously by several BSs. This is immediate if considering jointly several operator resources and umbrella layers. However, we quantify analytically the truth of this statement from a single operator point of view and a single layer of cells. This is perceived to be more realistic. In the third part, based on the quantitative knowledge of feasibility, the design and performance of the scheme is addressed. Traffic gain compared to a normal system is derived analytically and simulations are carried out for fine tuning and performance of different resource allocation algorithm. Finally we conclude on the engineering challenges for implementation such as the receiver's complexity and mobility handling and give a few typical yet interesting applications.

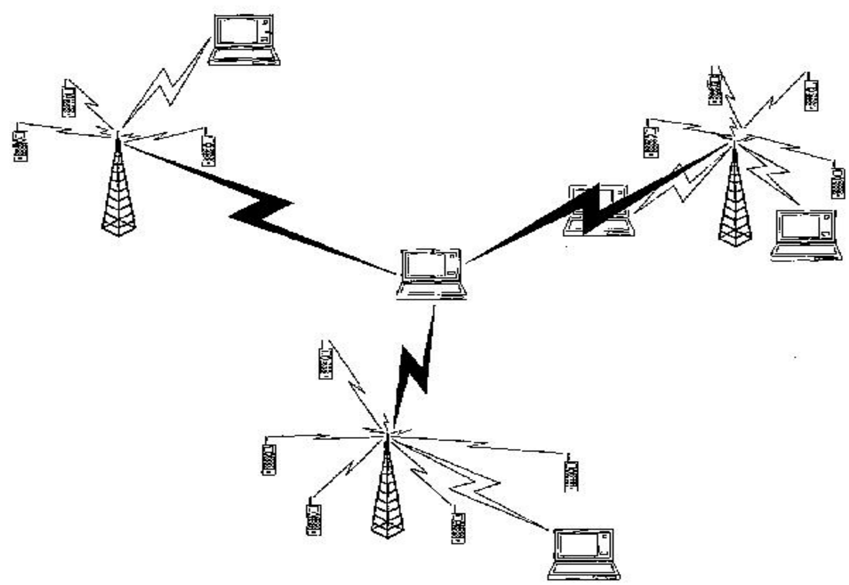

Figure A: multiple base-stations data-splitting

I.4. Major contributions

From a mathematical modeling point of view, this works has resulted in the development of several novel tools. A framework for solving joint coverage problems in the downlink is proposed in III.1.1. In a similar fashion, a new analytical approximation of the SIR at the mobile has been found, which proves to be accurate even for small reuse distances and when the mobile is located far from its BS. This was needed since the usual approximation which considers that all the interferers are at the reuse distance from the mobile can be very inaccurate in such cases. Finally as far as load-sharing analysis is concerned, this work introduces a very simple analytical approach allowing the derivation of the traffic gain. This analysis holds for symmetrical loads only but can be used for multi-slots data users. This approach is interesting since analytical work on load-sharing gain is usually very heavy and cannot be easily extended to data-users.

Apart from the analytical considerations, the main contributions of this work reside in two points. First it is proven that a mobile using adjacent cell as well as other operators' and umbrella cells can get a continuous connectivity with several BSs, and as such can make use of their resources to have a better service. Second, using this plurality of BSs, it is shown that a significant class of super-users can be integrated smoothly in the existing cellular infrastructure. Simultaneous data splitting from the different BSs using resources in a way that minimizes the impact on the system is found to give very good results, from the operator point of view. As a result this work can be seen as a method for giving good connectivity to mobile WLAN stations in an urban environment (in cars or buses).

CHAPTER II CONCEPTS AND BACKGROUND

This section gives an organized overview of related works found in the past literature, patent databases and commercial products. This review is by no way exhaustive and we only present relevant work for our study. Attentive readers who are familiar with the concepts introduced at the beginning of this chapter may want to skip directly to the summary at the end of the chapter. In a first part, we review some architectural considerations on data-splitting schemes. Motivations for multiple base-station service schemes are then presented: load-sharing and / or cell-site diversity. We finally introduce a multiple base-station scheme called Virtual Cellular Networks (VCN), whose architectural considerations are of interest for our work.

The concepts used in this work cover sometimes different realities. To avoid any misunderstanding, we specify here what is meant by “multiple base-stations service”, “data-splitting”, “load-sharing”, and “cell-site diversity”.

- Multiple base-stations service

This terminology will be used anytime to refer to a wireless communication system whereby the service to a Mobile Station (MS) is provided through more than one Base Station (BS). Usually within a wireless system, at a given time, a MS is served by only one fixed node of the network (BS), and while in motion seamlessly changes BS using a process called “Handover”. In itself the handover procedure is a multiple base-station service. What is meant by “service” can be resource allocation, simultaneous transmission, throughput optimization, and so on.

➢ <u>Data-splitting</u>

These words refer to any scheme whereby the information received at the MS have been split or striped through several links from distinct wireless access points (BS for example). It is obviously a multiple base-stations service. Note that no hypothesis is made on the nature of the several links. They can belong to different kinds of wireless systems. Figure II-1 illustrates the concept: solid lines represent wired links and dashed lines represent wireless links.

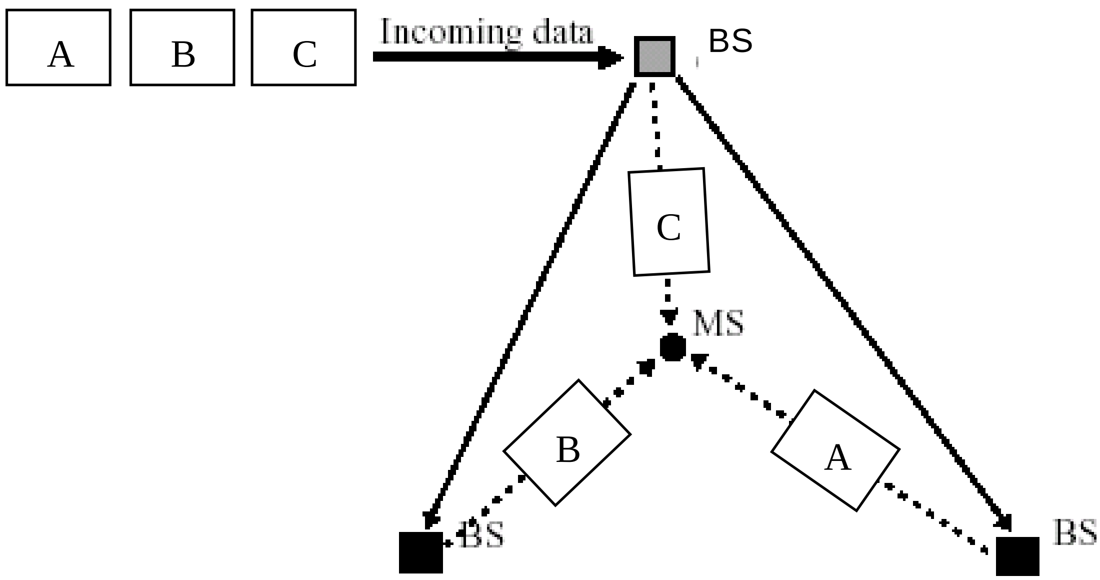

Figure II-1: data-splitting over wireless links

➢ <u>Load-sharing</u>

When a mobile user places a new call or setup a new link for data services, he is said to place a load to the serving node, that is, to the BS. In wireless systems, each BS has a certain amount of resources available to serve mobile users. This amount can be static or dynamic. Load-sharing refers to any situation whereby the resources potentially granted to a MS are shared by several BSs which can reach the MS. This can be done at two levels: either the MS can select dynamically its BS (load-sharing is then used because the MS will select its BS in order to optimize traffic balance between adjacent cells), or the MS can be served simultaneously by several BSs in order to avoid putting an excessive load to one BS. The target is load-sharing and the method here is data-splitting. This is again a multiple base-station service. This concept is related to traffic problems (congestion, quality of service).

➢ Cell-site diversity

Channel in wireless systems between MS and BS suffers from several impairments such as shadowing or multi-path fading. These kinds of impairment are a major problem in wireless communications systems and the design at the lower layers tries through specific coding / modulation to prevent its effects. Diversity can be used as well: one well known is antenna diversity where several adjacent antennas are used to provide a duplicate reception within the same site on the uplink, and to work out directionality on the downlink. Site diversity refers to a more general antennas diversity where several antennas from distinct sites receive the same uplink data (MS emission is so far omni-directional) and emit the same downlink information stream to the MS. Thus in both reception scheme (uplink and downlink), decision from several different sources can be used to make the final decision, providing a better performance (primarily a lower bit error rate). This is another kind of multiple base-station service. It is often referred to as macro-diversity.

II.1. Data-splitting over multiple links

This section reviews the proposition of data-splitting schemes in literature. The usual aim is improvement of throughput and/or reliability. The section does not deal with the physical layer feasibility and challenges, but rather with the architecture design issues and protocols. Example of such issues are interoperability with heterogeneous physical sub-systems (WLANS, cellular systems,…) and dynamic changes of links.

Splitting can be considered architecturally at different levels. The position of the data-splitting module for wired network within the ATM layer model is discussed in [7] through the example of ATM over SONET networks. From [7], Figure II-2 illustrates the different possibilities. Although we focus on wireless networks using different layer architecture, this example gives a good reference on the different way of implementing data-splitting.

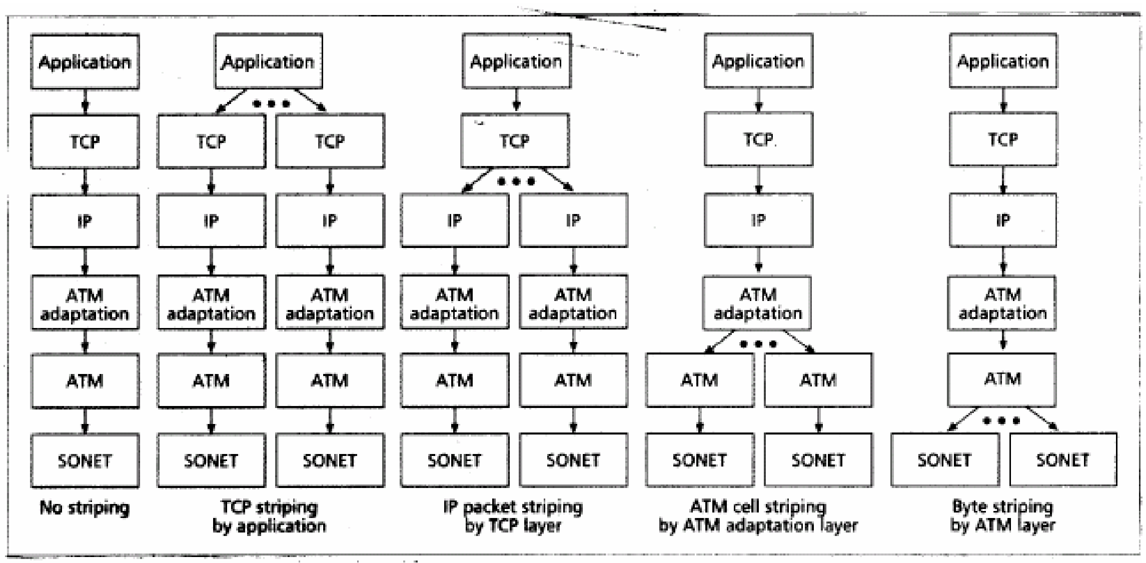

Figure II-2: position of the data-splitting module in the ATM model

II.1.1. Application / transport layer

As seen in Figure II-2, the first way of considering data-splitting is to create a specific application which opens several transport sessions (e.g TCP). As an example, a MacOS software [8] has been written which opens multiple sessions to a FTP/HTTP client to download a single file. It uses a specific command allowing downloading only a part of the file. The downloading time can be then reduced, because each virtual link downloads one part of the file. It was designed in order to bypass the per user bandwidth restrictions of file sharing servers. This concept is applicable for homogeneous or heterogeneous physical layers supporting the different links, as shown in Figure II-3. If the physical interfaces are homogenous (e.g cellular), this scheme does not really make sense, since it does not give room for resource allocation optimization. If on the contrary the physical interfaces are heterogeneous, this proposal is interesting from a super-user point of view since it definitely increases throughput or reliability. However, in a mobile wireless environment it raises numerous challenges. The application layer itself would have to be in charge of dynamically refreshing the links, managing the change of IPs, calculating the optimal amount of packets to give to each TCP session, etc. Besides, this solution works in a unidirectional context only.

As a conclusion, this splitting proposal is a good “do it yourself” method for usage across heterogeneous links. But in a way, it does not respect the layer philosophy since the application layer is now in charge of numerous operations which are lower layers specific.

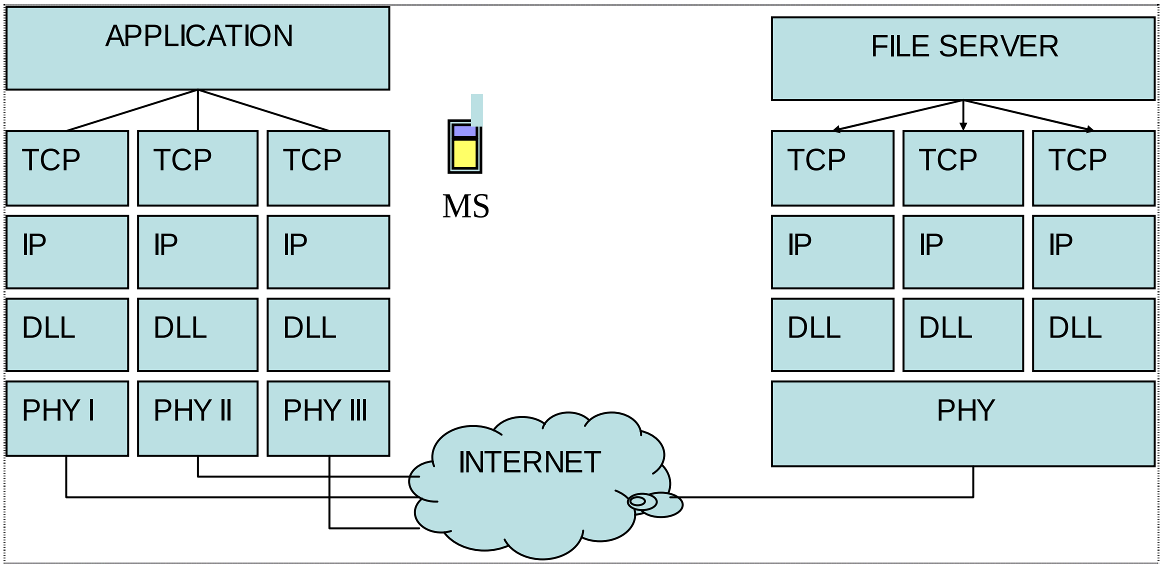

Figure II-3: splitting module at the application / transport layer

II.1.2. Transport / Network layer

From Figure II-2, the splitting module can be placed between the transport and the network layer. It means that the application opens one transport session which manages different IP interfaces. The mobile user is therefore assumed to be multi-homed. As a reminder, TCP cannot work with several IPs at the same time. Two proposals have been found which addresses the problem of multi-homing for wireless mobile clients.

➢ <u>Transport solution: SCTP</u>

This recently standardized transport [9][10] protocol is connection-oriented and can work over multiple IPs. At the beginning of the transmission, it initiates an "association setup" phase with its corresponding peer during which both peers exchange information about their different interfaces. The peers decide upon a "primary path" (a pair of IPs) over which to send the main stream of data. Other interfaces are used for retransmission or upon failure of the primary path. Data-splitting can be done with a slight modification of the protocol. Recently an extension to the protocol called Dynamic Address

Reconfiguration [11] has been written allowing real time changing of the interfaces and IPs within the association. Although the protocol was initially designed for reliable transport of SS7 signaling over wired networks, this recent change makes it very interesting for multi-homing in a mobile environment. Since then we have also started working [3] on the applicability of this protocol for wireless mobile host. SCTP is pushed by IETF to become the next standard transport protocol. It makes it a very good candidate for super-user multi-homed wireless hosts over heterogeneous links (GPRS+WLAN e.g.). A transport solution seems then to be best suited for splitting module as far as the multiple links used are heterogeneous. The major fact is that it is an end-to-end solution. That means first that it is very "cheap" for implementation and can be decently efficient at low cost, provided that SCTP is implemented widely. SCTP will be included in the new Linux Kernel 2.6. However, it means as well that if an interface is dropped, all the packets in the network going to it will be discarded. By the time both peers know that an interface is no longer valid and delete from the association, a lot of packets can be lost. This can be a problem with high mobility.

- <u>Network solution: tunneling</u>

Another interesting solution [12] is to design a mechanism at the top of the network layer which makes the multi-homing operations transparent to the transport layer, allowing therefore the use of TCP. This solution was specifically proposed for multi-homed wireless hosts with heterogeneous wireless links. The mechanism used tries to fool TCP by presenting/receiving from the transport layer only one kind of packet {TCP port number, IP source, IP destination}. However, when the module wants to send this kind of packet through another IP link, it encapsulates the previous packet and gives it to the network layer, which sends it then through another IP link. At the reception, the network layer des-encapsulates the received packet and gives a valid packet to TCP. This is basically an IP tunneling method. The scheme uses IP headers available space to exchange information about each other's interfaces. The main problem identified was the poor performance of TCP due to the characteristics of different links. It was solved by allowing the module to tune the packet sizes accordingly with the throughput of the link. This proposal is interesting but would require a redefinition of the IP layer operations.

The above mentioned schemes are good candidates for implementing super-user operations when dealing with heterogeneous physical layers. However, the focus of our work is to operate bandwidth aggregation within the same physical layer. Therefore the splitting module has to be placed at Layer 2. Since the same medium is used, the splitting has to be made in a way that optimizes resources allocation; therefore it should be an integrated mechanism within the MAC and DLL systems.

II.1.3. Network / Data link layer

Assuming the mobile has different links with different characteristics (for example several paths to distinct base-stations), [13] analyses different methods for sending packets through the different links in a way that optimizes the throughput. Three ways to send packets through different links are analyzed:

- Naïve: whenever a link is available it takes a packet in its queue and send it.
- Round-robin fashion
- Advance-sending: the module calculates the delay of each link and sends packets in a way that packets arrive almost in order (sender buffering).

Advance-sending is found to give the best results. This work focuses on the “sending packets” function of the splitting module. However, feasibility at the physical layer, motivations, and resource allocation problems are not addressed here.

As a conclusion, some data-splitting architectures have been very recently proposed for wireless systems. Good starting points have been identified for bandwidth aggregation with heterogeneous multiple links. As far as homogeneous links aggregation is concerned, very little work has been found and a lot of issues need to be analyzed, which will be carried out in the following sections. Having now a clear picture in mind about splitting operations, the next section addresses a multiple base-station service scheme called load-sharing.

II.2. Load-sharing in cellular networks

The previous section deals with data-splitting architectures and protocols, but does not address the motivation for such schemes. This section addresses a specific multiple base-station service called load-sharing which can be one motivation for data-splitting schemes. Most of the past work on load-sharing has been carried out for voice users in cellular networks. Voice users need one channel only, therefore there is no need for splitting. Splitting can be used when extending the load-sharing concept to multiple channel users. The idea of load-sharing is quite simple: the system tries to use several BSs to increase the pool of available resources for the MS, or more widely to enhance capacity / resource management / efficiency. A typical example of such a scheme is when the main serving cell is experiencing a high load; the MS can be reassigned to another server, or use several links from different BSs to increase its throughput without putting too heavy a load on one cell. Load-sharing is more obviously applicable to TDMA/FDMA systems because the resources of adjacent cells are distinct and can thus be shared. This is less obvious for CDMA systems, where each cell can use all the available resources.

II.2.1. Direct retry / handover on traffic

The simplest way of implementing load-sharing for voice users is to allow direct-retry and handover on traffic.

- **Direct retry** [14]. When a new call attempt is blocked, the MS is allowed to retry with the second best server. This assumes that when the call is blocked, it is because the cell is quite loaded.
- **Handover on traffic**. Equivalently, from the BS side, a heavily loaded BS can force a MS to handover to an adjacent less loaded cell, in order to balance the traffic.

These simple mechanisms allow a 10% increase in the accommodated traffic in a fixed channel assignment situation. This small gain is because the sharing strategies used are non-optimal, but rather best-effort.

II.2.2. Sector load-sharing

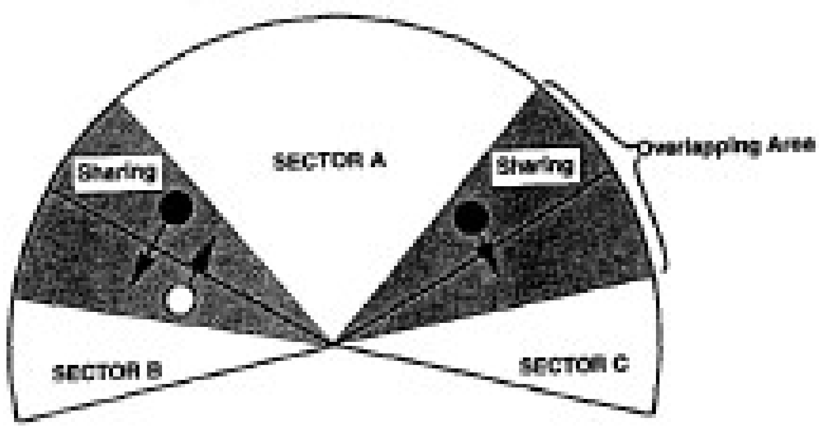

Figure II-4: sector load-sharing

Another simple mechanism was proposed in [15] based on adjacent sectors' load-sharing. In this scheme, the blocked traffic in each sector can be shared with the adjacent sector depending on its availability, as seen in Figure II-4 from [15]. The main claim here is simplicity of implementation (intra-cell hand-over only) compared to Hybrid Channel Assignment or Dynamic Channel Assignment (DCA), and the efficiency against Fixed Channel Assignment (FCA). The performance again is given in terms of blocking probability with different overlapping areas against Fixed Channel Assignment. The traffic gain is around 10% with an overlapping of 15%. Once again the sharing strategy is best-effort only (overflow accommodation).

II.2.3. Cell load-sharing

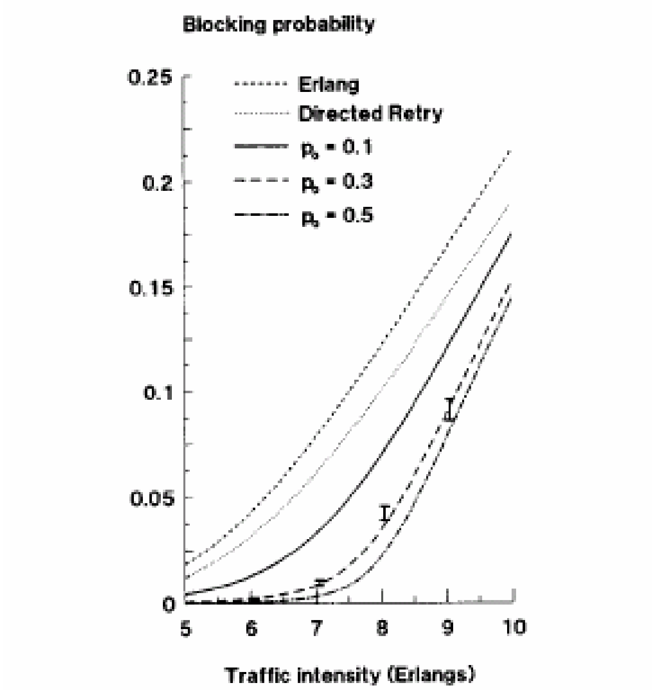

Figure II-5: cell load-sharing performance

Cell load-sharing has been proposed for voice users in [16][17]. The idea is to select the base-station serving the mobile in a way that enhances globally the resource allocation. Several strategies can be used. [16] implements an efficient global balancing solution with guard channels for users who can receive from one base-station only. The results are given in Figure II-5 from [16], *p* being the overlapping parameter. It can be seen that an overlapping of 30% gives a traffic gain of 35%, which is very significant. [17] proposes a direction predictive scheme to improve the base-station selection decision. It has to be noted that none of the above mentioned references addresses the issue of feasibility at the physical layer. The overlapping area is set as a parameter, supposedly known. Numerous patents on cell load-sharing for voice users have been obtained [18].

II.2.4. Cell load-sharing with data-splitting

This idea is an extension of the previous concept applied for multiple channel users, suitable therefore for our problem of super-users accommodation. As mentioned before, the user is granted several channels from distinct base-station in order to achieve a good throughput while distributing the load. The idea has been patented [19] only and nothing has been analyzed in term of feasibility, gain, design and applicability.

As a conclusion for this part, load-sharing is a well established idea for voice users in cellular systems. Its traffic gain can be very significant. It has come recently of interest to consider the application of the concept for super-user accommodation using data-splitting.

II.3. Cell-site diversity

Although it is not our main concern here, it has to be noted that the most explored application of multiple base-station service is diversity. Quite naturally, since the mobile antenna is so far omni-directional, several base-stations are likely to receive the signal and can combine these different versions to improve the decision [20][21]. A typical application is the soft-handover in IS-95 CDMA systems.

The idea, quite natural in the uplink, has recently received more attention in the downlink [22], with the generalization of directional antennas, and the promising future of smart-antennas. The idea here is to multicast the information or to select dynamically the BS on the downlink to provide diversity at the MS reception. The received power at the MS is the sum of the different powers. Good spectral efficiency can be achieved with sufficiently directional antennas. Cell-site diversity has been standardized as an implementation option in WCDMA [23][24].

II.4. Virtual Cellular Networks (VCN)

We present here a specific architecture which has been designed based on the multiple base-stations service concept. VCN [25][26][27] key elements are:

- Uplink cell-site diversity.
- No frequency planning, the channel assignment involves potentially several base-stations and is fully dynamic.
- Downlink multicasting and / or data-splitting.
- The set of cells able to receive uplink data creates a virtual cell. Each virtual cell is managed by a Centralized Base Station (CBS), which makes the final decision on the uplink, and distribute packets to the different BSs on the downlink.

Although VCN are not applicable to our work, since it defines its own multiple access and is not meant to be adapted to standard cellular systems, its architecture provides the first insight into multiple base-station handover procedures [27]. Among all the BSs of the virtual cell, one is chosen by the mobile as a Central Base-Station (CBS). The CBS has all the QoS queues and data link states of the several BSs communicating with the MS. As such, two distinct handover are possible:

- Radio handover: addition or removal of a BS within the virtual cell. This is managed by the CBS and can be triggered by the mobile.
- Buffer handover: change of CBS. The mobile chooses another BS to carry the centralized function.

Radio handover is fairly simple; it just involves addition or removal of the QoS queue and the data link states at the CBS, along with the usual radio procedures of a handover. Buffer handover is more complex. The new CBS must receive from the old one all QoS queues and links states, that is: packets sequence number, uplink Automatic Repeat Request (ARQ), and downlink buffers. Three buffer handover methods are proposed and analyzed:

- Dropping of all states: only the sequence numbers are transmitted. This is the simplest way. But it's quite inefficient because all the links have to be "re-built".
- Pre-transfer: a complete copy of the link states are transmitted, then the trigger is made on an ON / OFF basis. This is efficient but quite complex. It can become very burdensome in signaling in a "ping-pong" scenario. Therefore it is very suited for a predictive scheme.
- Post-transfer: the uplink stays in the old CBS for a while for ARQ completion, and the downlink is immediately transferred to the new CBS. This method is very efficient and of high complexity.

The different handover methods and their applicability are summarized in Table II-1 from [27].

Method	Complexity	Performance	Uses
Dropping	Low	Low	WLAN
Pre-transfer	High	High	Highway, trains
Post-transfer	High	High	Indoor, urban

Table II-1: overview of different buffer handover mechanisms

As a conclusion, interesting propositions have been made for multiple base-stations handover in VCN. This proposal can be applicable to our study in the architectural considerations.

II.5. Summary

Data splitting schemes have been studied mainly for wired networks [7][8][9] and more recently for wireless networks. A few interesting studies [10][11][12] presents partial solutions for heterogeneous bandwidth aggregation putting the splitting module between the transport layer and the network layer (SCTP based mechanism, or TCP transparent IP tunneling). These schemes can be suitable for a peer-to-peer architecture and are good candidates for implementing a super-user class using different physical layers. Data-splitting for homogenous bandwidth aggregation from different access points has to be integrated at the MAC/DLL layer, in order to perform efficient resource allocation. The aggregation here is done within the base-station sub-system of a cellular network and is transparent to the TCP/IP plane. One proposal [13] analyses packet sending strategies over multiple cellular links. Data splitting over homogeneous links can be motivated from a resource allocation point of view as a way to achieve load-sharing. It has to be noted that a well known alternative to data-splitting in using multiple base-stations to enhance the performance at the mobile is cell site diversity [20]-[24] whereby instead of splitting the data, multicasting is used in order to improve the performance at the reception.

Load-sharing is a well known and applied concept for voice users in cellular networks. Simple solutions [14][15] are based on overflow accommodation by adjacent cells or sectors: direct retry, handover on traffic, and sector load-sharing. More optimal solution achieve efficient load balancing using multiple base-stations [16][17][18]. The traffic gain achieved is as high as 35% for a 30% overlapping of cells. Our idea is to extend the load-sharing concept to multiple channels users using data-splitting. A patent has also been obtained on this scheme [19], but no analysis, applicability statement, design or performance has been carried out so far.

Finally, an early multiple base-station architecture called Virtual Cellular Networks [25][26][27] presents the first insight in multiple base-stations handover procedures. An interesting centralized scheme is also introduced.

CHAPTER III JOINT COVERAGE STATISTICS IN SINGLE-LAYERED CELLULAR NETWORKS

As mentioned before, the feasibility and efficiency of the proposed scheme depends heavily on the possibility for the mobile user to receive simultaneously from several base-stations. If umbrella cells are deployed (such as Ericsson HCS in Figure III-1 from [28]), it is very likely that the mobile station can receive correctly from at least 2 BSs regardless of its position. Similarly if we assumes that the mobile client can simultaneously make use of several operator resources (super-user point of view), the number of available base-stations is potentially high. However, umbrella cells might be discontinuous and being able to use several operators' base-stations is technically challenging. Therefore the purpose of this section is to quantify the ability of a mobile client to be jointly covered by several base-stations of the same layer of cell from a single operator.

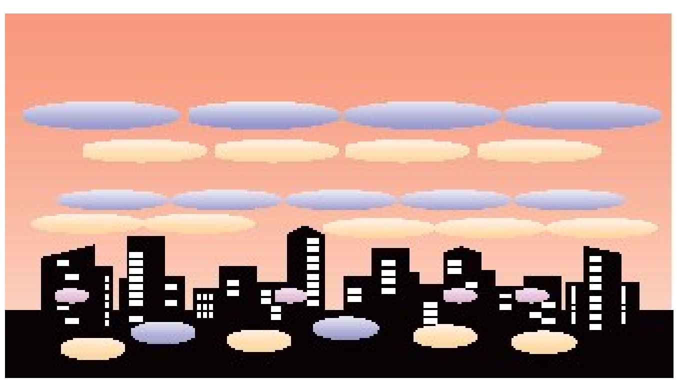

Figure III-1: Ericsson multilayered hierarchical cell structure (HCS)

III.1. Assumptions and analytical framework

Analysis of the coverage of one cell under co-channel interferences and log-normal shadowing is well known [29]-section II. To the author's knowledge, joint coverage statistics from a plurality of BS's have received little attention in the literature.

Joint coverage has been studied from the geometrical overlapping point of view in [30]-[31]. In these papers, geometrical overlapping areas are defined and calculated as a function of the coverage radius. This basic parameter, distinct from the cell radius, is assumed to be known. Such an approach implicitly assumes deterministic path loss model and worst-case co-channel interferences. A few statistical studies [32]-[33] explore the joint coverage problem based on the received power distribution. Here, the mobile is said to be covered if the received power is above a certain threshold. Joint coverage from N radio transmitters in a mobile radio system has been briefly addressed in [34] without the presence of interferers. Finally in [35], a statistical approach based on the received signal-to-interference ratio (SIR) distribution is used. In this paper, the cellular layout is linear (one dimension).

The work presented in this section is motivated by the following facts:

1) Although the above-mentioned works give interesting insight into the joint coverage problem, there are no works or experimental benchmarks available giving clear reference figures for joint coverage in typical cellular layouts. More generally, *reference results* are needed as a function of cellular and network parameters.

2) Joint coverage can be in a first approach restricted to overlapping area. However this does not give a realistic picture of the problem since in urban environment, due to the complex geographical layout, a mobile can receive a good signal from a

remote BS, and a bad signal from the closest BS. Therefore a statistical approach with shadowing has to be introduced.

3) The joint coverage area is more accurately defined by a signal-to-interference (SIR) criterion than a received power criterion, because a mobile will be said to have a proper communication with several BSs if the SIR received from them exceed a certain threshold. Therefore, throughout this section, a SIR based approach will be taken.

4) Finally, joint coverage figures are needed here as parameters for the next section; therefore simple analytical tools allowing quick evaluation are very valuable and need to be developed.

The chapter is organized as follows. In this sub-section system model, main assumptions and general expressions of the joint coverage statistics are presented. Sub-sections III.2 and III.2 focus on joint coverage figures for a 2 and 3 BSs subsystem. In sub-section III.2 an analytical expression for the normalized joint coverage area is derived under deterministic path loss model, worst case co-channel interferences, and non-sectorized cellular layout, extending the work done in [30]. This expression is based on a new approximation of the SIR received at the mobile. In sub-section III.2, joint coverage figures are analyzed under more realistic configuration, i.e log-normal shadowing, sectorization, and non-worst case co-channel interference. Emphasis is made on typical EDGE layout 4/12 and 3/9 with realistic assumptions on the cells load. Section III.2 concludes on the feasibility of the load-sharing scheme.

III.1.1. System model

The system studied is a *n* adjacent BSs subsystem. We define an elementary area whereby the mobile can jointly be served by its *n* closest BSs . In other words, a "*n BSs* " subsystem in the cellular network is the area mathematically defined by the "unique set of points whereby the *n* BSs considered are the *n* closest BSs ". Figure III-2 provides illustrations for $n = 2$, 3 and 4. The grey area is the unique set of points whereby the *n* BSs represented are the *n* closest to these points among all other sets of *n* BSs . It's important to notice for the following development that this definition leads to the creation of subsystems that are non-overlapping and define a complete "pavage" of the space on top of the hexagonal division. That is, for any two *n* BSs subsystems whereby the two sets of BSs considered differ at least by one, the corresponding geometric areas as defined are non-overlapping. Moreover, any point of the space belongs at least to one subsystem. Therefore, any point of the space belongs to one and only one subsystem as defined previously. Practically only the few closest BSs are able to provide a significant SIR to the mobile, therefore the interesting values of *n* are typically 2, 3 or 4.

The previous definition of subsystems simplifies the analysis since now only one subsystem characterizes the joint coverage problem over the whole cellular network. It represents in a way the equivalent of a "cell" for multiple BSs coverage problems. In a single BS problem, the coverage ratio is obtained by integration over a cell. Similarly here, the multiple BSs joint coverage will be obtained by integration over a multiple BSs cell. It is clear that joint coverage from the *n* BSs of the subsystem can be obtained sometimes outside the subsystem, but it is not of much interest.

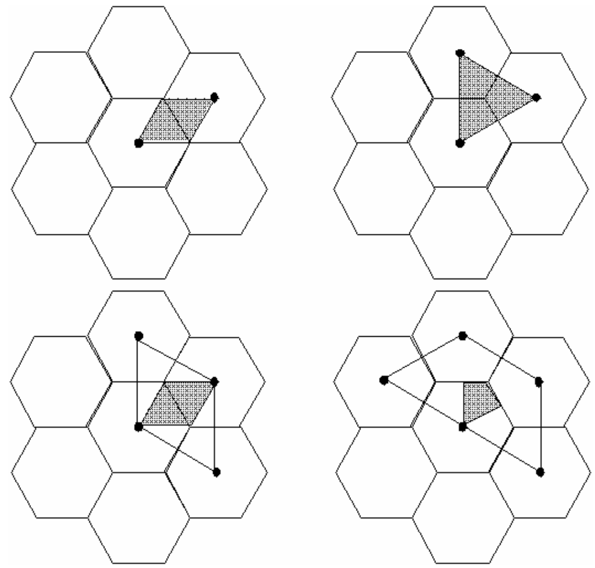

Figure III-2: *n* BSs subsystem. Illustration for *n* = 2, 3, 4, 5

III.1.2. Assumptions

The mobile's received SIR on the downlink is analyzed through log-distance and lognormal path loss models in co-channel interferences. As it's a "long-term" joint coverage figure which is of interest, fast fading is not taken into account. Shadowing, path loss exponent and co-channel interferences are the main factors which influence the "long-time" averaged received SIR at the mobile [36][37].

The study focuses on co-channel interference, and therefore the system is assumed to be interference limited (thermal noise is neglected) [38]. Furthermore, following [38], only first-tier co-channel cells are considered. We also assume that all BSs emit the same power. Throughout this thesis, it is generally assumed that the average network loads experienced by all the cells are equal.

III.1.3. General expressions

The SIR received at the mobile from the *k*-th BS of the *n* BSs subsystem will be denoted by Γ_k and is given by [39]:

$$\Gamma_k = \left(\sum_{i=1}^{m_k} 10^{w_{ik}/10} \left(\frac{r_k}{d_{ik}} \right)^{\gamma} \right)^{-1} \quad \text{(III-1)}$$

where m_k is the number of active co-channel interferers for cell *k*, r_k is the distance from base station *k* to the mobile, d_{ik} is the distance from the *i*-th co-channel cell of cell *k* to the mobile, γ is the path loss exponent, $w_{ik} = y_{ik} - x_k$ where x_k is the random variable (RV) modeling the shadowing of the signal from BS *k* and y_{ik} is the RV modeling the shadowing of the signal from the *i-th* interferer of cell *k*. Both x_k and y_{ik} are 0 mean Gaussian RV with variance σ^2. For a given *k*, x_k and y_{ik} are usually assumed to be statistically independent. Therefore $w_{ik} = y_{ik} - x_k$ is a 0 mean Gaussian random variable with variance $2\sigma^2$. Distance parameter will be represented by (*x,y*) or equivalently (r, θ).

Many metrics for quantifying the joint coverage are relevant, depending on their intended usage. It may be the sum of the received SIR exceeding a threshold (suited for macro diversity problems). It can be as well requesting one threshold per SIR. In this thesis the mobile is said to be jointly covered by the *n* BSs if the SIR received from all the BSs at the mobile exceed a threshold *z*. It is clear that this metric is not universal, but it best fits the general concept of overlapping. Therefore we define the probability of joint coverage from *n* BSs at the mobile given the mobile's location and the distribution of co-channel interferers as follows:

$$P_{n\text{cov}|(x,y),(M_1,M_2,...,M_n)} = P[\Gamma_1(x,y) \geq z, \Gamma_2(x,y) \geq z,..,\Gamma_n(x,y) \geq z] \quad \text{(III-2)}$$

where M_k denotes the RV defined as the number of active co-channel interferers of cell *k* taking the values m_k.

The Γ_k are random variables due to two random dependencies: first the number of co-channel interferers M_k is a RV depending on the network load, second the shadowing w_{ik} is random as well. The RV's $\{M_k\}$ are independent because the set of co-channel interferers for distinct BSs of the *n* BSs subsystem are distinct as well. This hold as far as the *n* BSs of the subsystem operate on different sets of frequencies that belong to the same cluster. This is a reasonable assumption for small *n.* For a given *k*, it's usually assumed that the $\{w_{ik}\}$ are statistically independent. We extend here this assumption for different *k,* that is, we assume that all the paths of the signals from the serving BSs as well as from the interfering ones experience independent shadowing. The shadowing correlation depends on the angular separation of the paths. In Figure III-3 all the paths from the serving BSs as well as from the interfering ones are represented for a two BSs subsystem in a symmetrical 1/7 layout. The grey cells represent the co-channel cells of BS 2, the dotted cells represent the co-channel cells of BS 1. It can be seen that the angular separation between two adjacent paths is still significant.

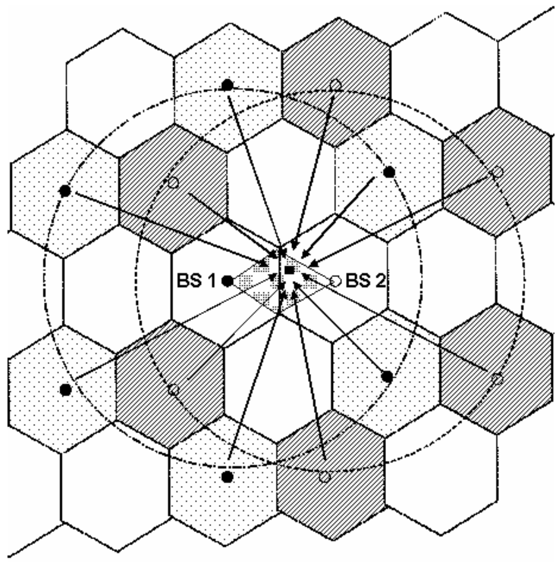

Figure III-3: Angular separation of all the paths of the different received signals at the mobile for a two BSs subsystem.

However increasing the number of BSs in the subsystem will lead to increasingly small angular separation between two paths, therefore assumption of independency can be rather tricky. Therefore, we make this assumption for small *n* only.

Assuming independence of $\{w_{ik}\}$ for any *i, k* and independence of $\{M_k\}$ for any *k*, the RV's $\{\Gamma_k\}$ are then statistically independent. Equation (III-2) can be then simplified as follows:

$$P_{n\,\mathrm{cov}|(x,y),(M_1,M_2,\ldots,M_n)} = \prod_{k=1}^{n} P[\Gamma_k(x,y) \geq z] \qquad \text{(III-3)}$$

Taking the expected value of (III-3) with respect to the distribution of interferers, that is the random variables $\{M_k\}$, *the joint coverage probability at the mobile given the location* is:

$$P_{n\,\mathrm{cov}|(x,y)} = \sum_{m_1=1}^{M} \sum_{m_2=1}^{M} \dots \sum_{m_n=1}^{M} \left(\prod_k P[\Gamma_k(x,y) \geq z] P[M_k = m_k] \right) \quad \text{(III-4)}$$

$P[M_k = m_k]$ is the probability that the number of active co-channel interfering cells of cell k is m_k. As the system is considered to be interference limited, it is assumed that there is at least one active co-channel interfering cell. M is the maximum number of co-channel interfering cells in the first tier (6 for a non-sectorized cellular layout). Therefore $1 \leq m_k \leq M$.

Following [40], let p denote the probability that a co-channel interferer is active (load factor of the cell). If a new call is randomly affected to one of the available channel within the resources of the cell, p represents as well the average number of occupied channels, normalized to the total number of channels. In an Erlang B with lost calls cleared model [39], the average number of users in the system is the mean arrival rate times the mean service time, by Little's law. The value of p is therefore directly linked to the carried load for a specific Grade of Service (GoS). As we assumed that the average network load is identical in every cell, p can be considered as a traffic parameter for the whole system. Assuming a GoS of 1%, typical values of p range from 0.4 to 0.6 for a 10 to 20 channels cell. Specific values of p can be used to simulate worst case conditions (p=1), or temporary light load conditions (p=0.2). However, p is a constant parameter since it represents the average carried load and as such already integrates traffic variations. With p defined as above, M_k follows a binomial distribution that we normalize to the probability that at least one interferer is active. Thus:

$$P[M_k = m_k] = \left[\binom{M}{m_k} p^{m_k} (1-p)^{M-m_k} \right] / \left(1-(1-p)^M\right) \quad \text{(III-5)}$$

Spatial average of the joint coverage probability given the location is obtained [32] by taking the expected value of (III-5) assuming the mobile can be anywhere within the *n* BSs subsystem with a probability density *dxdy/A*, where *A* is the total area of the *n* BSs subsystem:

$$P_{n\,\mathrm{cov}} = \frac{1}{A} \iint_{(x,y)\in A} P_{n\,\mathrm{cov}|(x,y)}\, dxdy \quad \text{(III-6)}$$

$P_{n\,\mathrm{cov}}$ represents then the percentage of the area *A* where the mobile is jointly covered by the *n* BSs of the subsystem. Due to our definition of subsystem, $P_{n\,\mathrm{cov}}$ represents as well for a mobile regardless of his location within the whole cellular network (not only within *A*) the probability of being jointly covered by its *n* closest BSs . Therefore we equivalently call $P_{n\,\mathrm{cov}}$ *normalized joint-coverage area*.

Once again this definition assumes that the average network loads are identical in every cell. As such it can be assumed that the user arrival is spatially uniformly distributed over the sub-system. This definition would fail when dealing with asymmetric average loads.

The following sections assume a 2 and 3 BSs subsystem, as any bigger subsystem is not likely to provide significant joint coverage to the mobile.

III.2. Analytical derivation for worst-case co-channel interferences and symmetrical cellular layout

This section provides an analytical figure for the normalized joint coverage area (III-6) for a 2 or 3 BSs subsystem. Equation (III-6) can be analytically simplified under deterministic path-loss model, worst-case co-channel interferences and non-sectorized cellular layout using geometric arguments. This aims to provide a convenient tool to evaluate quickly the normalized joint coverage area and to analyze the influence of the reuse ratio.

III.2.1. General expressions for a 2 and 3 BSs subsystem

Under the assumptions mentioned above, the SIR from (III-1) simplifies to:

$$\Gamma_k = \left(\sum_{i=1}^{M} \left(\frac{r_k}{d_{ik}} \right)^{\gamma} \right)^{-1} \tag{III-7}$$

As the path-loss model is deterministic here, the probability to receive an SIR above a threshold z is a simple step function:

$$P[\Gamma_k(x, y) \geq z] = u\left(\Gamma_k(x, y) - z\right) \tag{III-8}$$

Under worst case interferers' situation, (III-4) and (III-6) for a two BSs subsystem (area A_2) simplifies to:

$$P_{2\,\mathrm{cov}|(x,y)} = u\left(\Gamma_1(x, y) - z\right).u\left(\Gamma_2(x, y) - z\right) \tag{III-9}$$

$$P_{2\,\mathrm{cov}} = \frac{1}{A_2} \iint_{(x,y)\in A_2} u\big(\Gamma_1(x,y) - z\big).u\big(\Gamma_2(x,y) - z\big)dxdy \qquad \text{(III-10)}$$

Extension of the previous expression for a 3 BSs subsystem is straightforward:

$$P_{3\mathrm{cov}} = \frac{1}{A_3} \iint_{(x,y)\in A_3} u\big(\Gamma_1(x,y) - z\big)u\big(\Gamma_2(x,y) - z\big)u\big(\Gamma_3(x,y) - z\big)dxdy \qquad \text{(III-11)}$$

Rather than trying to simplify (III-10) and (III-11) or perform lengthy numerical integration, we try here to express them with geometrical considerations. The spatial integration of the joint-coverage probability is as well the ratio of the "overlapping" area over the subsystem area. Therefore if we are able to calculate geometrically the joint coverage area, dividing the result by the subsystem area A will give the figure. This area is basically the intersection of the coverage areas of the BSs of the subsystem.

III.2.2. Geometrical joint coverage area

The boundary of the area covered by a cell under deterministic path-loss model is given by the set of points (r,θ) so that $\Gamma_k(r,\theta) = z$ where z is the threshold requested at the mobile. Under the assumptions made in this section (worst-case interferences, symmetrical layout and deterministic path-loss model), the SIR can be approximated as an invertible function of r only. This is shown in the next section. Therefore the boundaries of the area covered by a cell are approximated here as circular arcs whose radius can be obtained analytically. This leads to a very simple joint-coverage geometrical area. Figure III-4 represents this area for a 2 and 3 BSs subsystem. The area is centrally symmetric with respect to the center of the subsystems since all the BSs of the subsystem experience similar worst-case interferer situation.

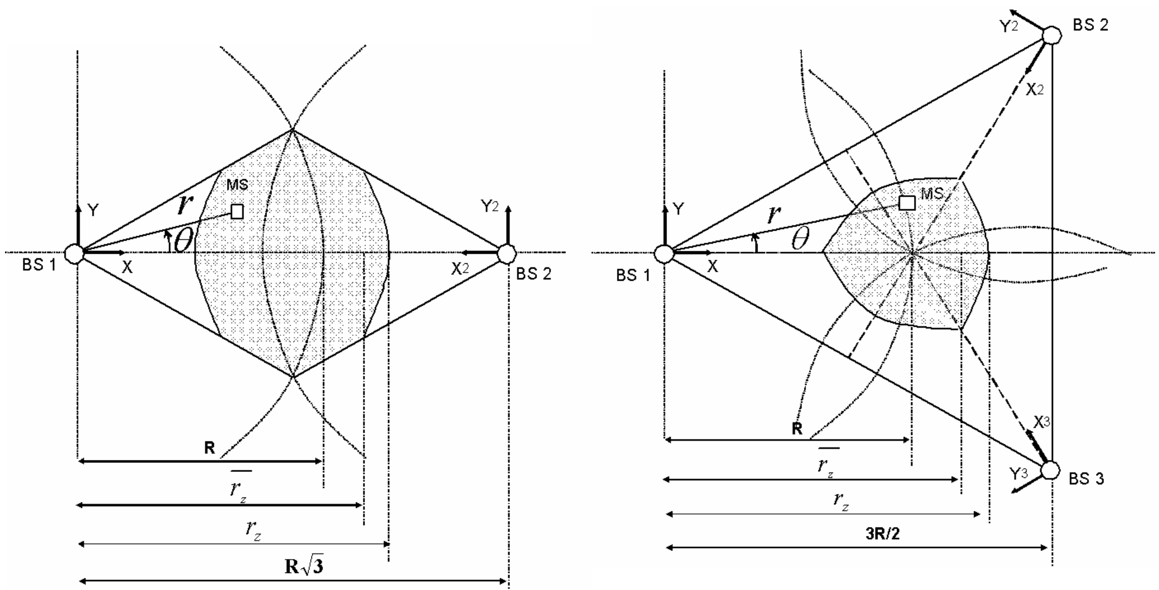

Figure III-4: joint coverage areas for a 2 and 3 BSs subsystem

The area for 2 BSs from Figure III-4 normalized to the subsystem area is found to be:

$$\begin{cases} A_2(r_z) = 1 - \dfrac{4}{\sqrt{3}}\left(\sqrt{3} - \dfrac{\overline{r_z}}{R}\right) + \dfrac{4}{\sqrt{3}R^2}\left(r_z^2 \arccos(\dfrac{\overline{r_z}}{r_z})\right) \\ \qquad\qquad \text{for} \quad R \le r_z \le \sqrt{3}R \\ A_2(r_z) = \dfrac{4}{\sqrt{3}R^2}\left[r_z^2 \arccos(\dfrac{\sqrt{3}R}{2r_z}) - \dfrac{R\sqrt{3}}{2}\sqrt{r_z^{\,2} - 3R^2/4}\right] \\ \qquad\qquad \text{for} \quad R\sqrt{3}/2 \le r_z < R \end{cases} \tag{III-12}$$

where $\overline{r_z}$ is the chord parameter given by:

$$\overline{r_z} = \frac{R\sqrt{3}}{4} + \frac{\sqrt{12r_z^2 - 9R^2}}{4} \tag{III-13}$$

and r_z is solution of the equation $\Gamma_k(r) = z$.

The area for 3 BSs from Figure III-4 normalized to the subsystem area is found to be:

$$
\begin{cases}
A_3(r_z) = \dfrac{4}{R^2\sqrt{3}}\left[r_z^2 \arccos(\dfrac{\overline{r_z}}{r_z}) - \sqrt{3}R\left(\overline{r_z} - R\right)\right] \\
\qquad\qquad\qquad \text{for} \quad R \le r_z \le 3R/2 \\
A_3(r_z) = \dfrac{4}{R^2\sqrt{3}}\left[r_z^2 \arccos(\dfrac{\overline{r_z}}{r_z}) - \sqrt{3}R\left(\overline{r_z} - R\right)\right] \\
\qquad - \dfrac{4}{\sqrt{3}R^2}\left[r_z^2 \arccos(\dfrac{3R}{2r_z}) - \dfrac{3R}{2}\sqrt{{r_z}^2 - 9R^2/4}\right] \\
\qquad\qquad\qquad \text{for} \quad 3R/2 \le r_z < \sqrt{3}R
\end{cases}
\tag{III-14}
$$

where $\overline{r_z}$ (see Figure III-4) is the chord parameter given by:

$$
\overline{r_z} = \frac{3R}{4} + \frac{\sqrt{4r_z^2 - 3R^2}}{4} \tag{III-15}
$$

III.2.3. SIR approximation

From (III-12) and (III-14) an expression for r_z has to be found, meaning that the SIR has to be inverted. In a general case, the SIR is a complex function of r and θ and cannot be inverted. The usual approximation of the SIR assumes that all the co-channel interferers are at the reuse distance D to the mobile. This approximation is invertible and valid for $r/D<<1$, that is when the reuse distance is big, or when the mobile is located close to its BS. However in the present situation, the SIR is needed as well when the mobile is located out of its cell, therefore this approximation can become quite inaccurate especially under small reuse distance.

The usual approximation is given by [29]:

$$\Gamma(r) = \frac{1}{M}\left(\frac{D}{r}\right)^{\gamma} \tag{III-16}$$

Equation (III-14) actually comes from the 0-order term of the Taylor expansion of Γ^{-1} in r/D around 0. We seek here to get a higher order expansion of Γ^{-1} in r/D around 0 that allows for an extended approximation. This result leads to an accurate invertible figure for the SIR when the mobile is located anywhere within the whole 2 or 3 BSs subsystem.

The distance d_i from the co-channel interferer i to the mobile obeys the cosine rule:

$$d_i = (r^2 + D^2 - 2rD\alpha_i(\theta))^{1/2} \tag{III-17}$$

From (III-12), Γ^{-1} is a function of $d_i^{-\gamma}$, which can be written as:

$$d_i^{-\gamma} = D^{-\gamma}\left[1 - 2\alpha_i(\theta)(\frac{r}{D}) + (\frac{r}{D})^2\right]^{-\gamma/2} \tag{III-18}$$

Expanding it to 2[nd] order in r/D around 0:

$$d_i^{-\gamma} = D^{-\gamma}\left[1 + \gamma\alpha_i(\theta)(\frac{r}{D}) + (\frac{\gamma(\gamma+2)}{2}\alpha_i^2(\theta) - \frac{\gamma}{2})(\frac{r}{D})^2\right] \tag{III-19}$$

Therefore Γ^{-1} can be approximated by:

$$\begin{aligned}\Gamma^{-1} &= \sum_{i=1}^{M}(\frac{r}{d_i})^{\gamma} \\ &= M\left(\frac{r}{D}\right)^{\gamma}\left(1 + \gamma(\sum\frac{\alpha_i(\theta)}{M})(\frac{r}{D}) + (\frac{\gamma(\gamma+2)}{2}(\sum\frac{\alpha_i^2(\theta)}{M}) - \frac{\gamma}{2})(\frac{r}{D})^2\right)\end{aligned} \tag{III-20}$$

Under worst-case interference situation and non-sectorized layout, it can be shown (Appendix A) that:

$$\begin{cases} \sum \dfrac{\alpha_i(\theta)}{M} = 0 \\ \sum \dfrac{\alpha_i^2(\theta)}{M} = \dfrac{1}{2} \end{cases} \tag{III-21}$$

Therefore the extended approximation can be simplified from (III-20) to:

$$\Gamma(r) = \frac{\dfrac{1}{M}\left(\dfrac{D}{r}\right)^{\gamma}}{1 + \dfrac{\gamma^2}{4}\left(\dfrac{r}{D}\right)^2} \tag{III-22}$$

The extended approximation in (III-22) is very valuable. First, it is very accurate even out of the cell (i.e for r/R>1). Second, it is invertible for a typical value of the path loss exponent γ = 4. Inversion of Γ for this value requires solving a 3rd order polynomial equation. The exact worst-case SIR (III-7) and the two approximations (III-16) and (III-22) are plotted in Figure III-5 for γ = 4 and cluster sizes of 4, 7 and 12. For illustration, the mobile is taken on the y = 0 line. The maximum distance between the mobile and any BS within a two or three BSs subsystem is $\sqrt{3}R$. From Figure III-5 it can be seen first that the usual approximation tends to be very inaccurate for $r/R>1$ especially for small reuse distance. The extended approximation is very accurate within the subsystem. For a small reuse distance and at the boundary of the subsystem, this accuracy decreases significantly (2 dB of error at the worst situation). Still, the reference for non-sectorized layouts is typically 1/7, for which this approximation is accurate (less than 0.5 dB of error at worst).

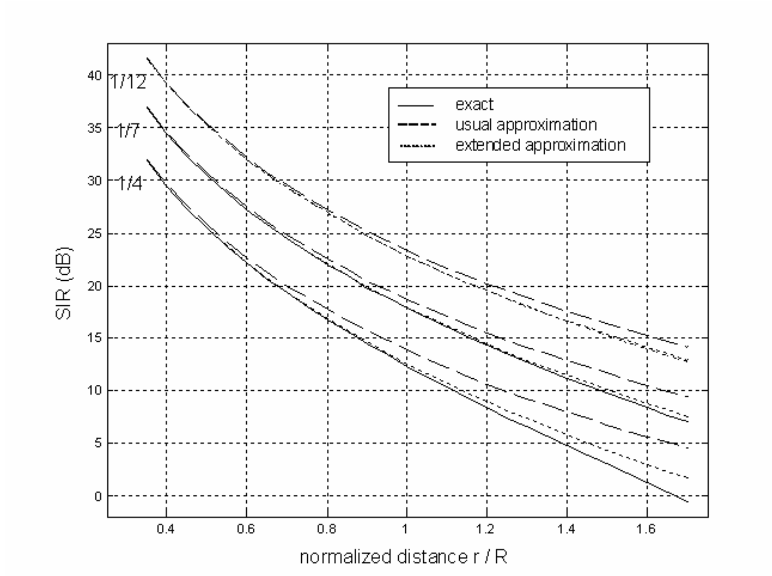

Figure III-5: SIR and its approximations with respect to the mobile's location

Now given a requested SIR threshold z (dB), the equation $\Gamma_k(r) = z$ can be inverted with the extended approximation (III-22). The inversion of (III-22) leads to solving for the root r_z of a 3rd order polynomial in $(r/D)^2$:

$$16\left(\frac{r_z}{D}\right)^6 + z\left(\frac{r_z}{D}\right)^4 + \frac{1}{M} = 0 \qquad \text{(III-23)}$$

It's known that it's possible to express analytically the roots of a 3rd order polynomial. The unique real root r_z here is found to be:

$$r_z = \frac{\sqrt{3}}{6} D\left(\frac{X^2 + w^2 M^2 - wMX}{wMX}\right)^{1/2} \qquad \text{(III-24)}$$

where X and w are given by:

$$\begin{cases} X = \left[-w^2 M^2 \left(wM - 216 - 12\sqrt{324 - 3wM}\right)\right]^{1/3} \\ w = 10^{\frac{z}{10}} \end{cases} \quad \text{(III-25)}$$

III.2.4. Worst-case symmetrical joint coverage probability

The spatial averages of the worst-case symmetrical joint coverage probabilities for a 2 and 3 BSs subsystem are obtained by using the normalized areas $A_2(r_z)$ and $A_3(r_z)$ from (III-12) and (III-14). Here r_z is given by (III-24) as obtained from the extended SIR approximation (III-22). Since the reuse distance *D* is equal to *R.Q* where *Q* is the reuse ratio, an attentive look at the expressions for r_z, $A_2(r_z)$ and $A_3(r_z)$ reveals immediately that the probability obtained is independent of the cell radius *R.* Therefore the analytical expressions found for the joint coverage probabilities are functions of the reuse ratio *Q* and the threshold requested *z.*

The joint coverage probabilities from (III-12) and (III-14) for a 2 and 3 BSs subsystem are plotted in Figure III-6 as a function of the requested threshold for a 1/7 layout. Analytical results are compared with numerical integration from the exact expressions (III-10) and (III-11). Figure III-7 presents analytical results for the joint coverage probabilities as a function of the reuse ratio. Vertical dash-dotted lines represent typical values of the reuse ratio. The requested threshold *z* is set at 15 dB.

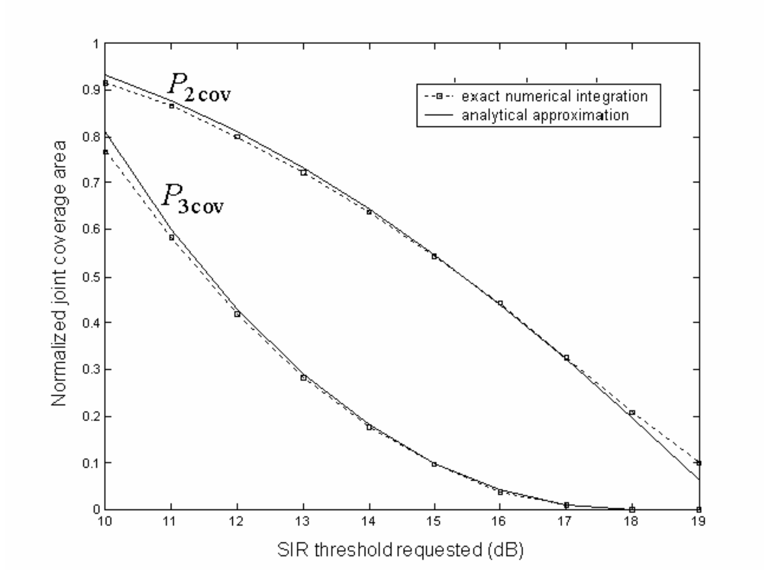

Figure III-6: normalized joint coverage areas with respect to the SIR threshold requested at the mobile

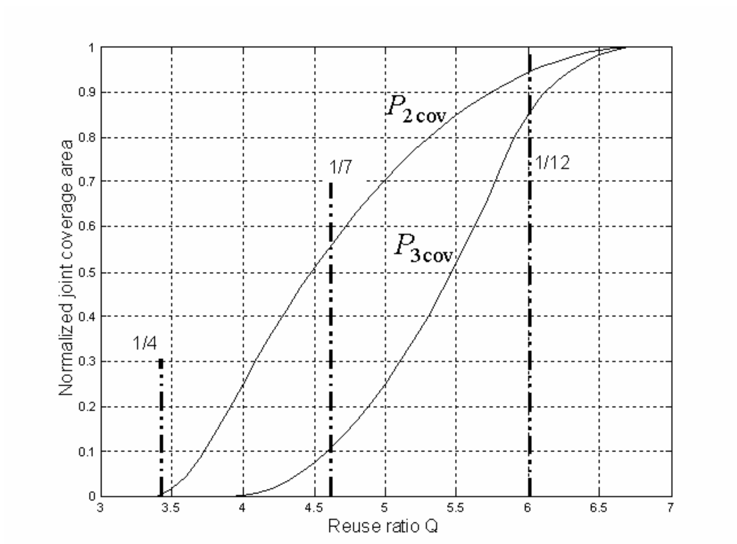

Figure III-7: analytical normalized joint coverage areas with respect to reuse ratio *Q*

As expected, the normalized joint coverage area is significantly higher for 2 BSs than 3 BSs . From Figure III-6, it can be seen that the analytical approximations match closely the numerical integrations of the exact expressions. As expected, the normalized joint coverage area is a decreasing function of the requested threshold (Figure III-6) and an increasing function of the reuse ratio (Figure III-7). Under worst-case interferences but without shadowing loss, the probability for a mobile in a 1/7 cellular system to receive a SIR of 15 dB from 2 BSs is 55%, and 10% from 3 BSs. Under less stringent requested SIR, say 10 dB, the probabilities are as high as 93% and 80%.

The aim of this section is to provide convenient tools for worst-case evaluation of the joint-coverage probabilities. Influence of the threshold requested and the reuse ratio could then be analyzed. However, they are restricted to Line Of Sight (LOS) conditions, symmetrical cellular layouts, and worst-case interference conditions. Firstly, channel conditions in urban environment cannot be accurately described with a LOS model. Indeed the best BS from the SIR point of view may not be the closest and as such joint coverage can be obtained even when located near to a BS. This interesting property can be quantified by introducing log-normal shadowing. Secondly, most cellular networks use sectorized antennas nowadays. Typical EDGE layouts [42] are sectorized 3/9 or 4/12 frequency reuse. As such these reference layouts need to be studied. Finally, in sectorized layout, the maximum number of co-channel interferers is typically 3 or 4. The impact of network load (i.e if these interferers are active or not) on the joint coverage probabilities becomes very significant. Therefore any variation in the number of interferers influences significantly the received SIR and then the joint coverage probabilities. It is therefore necessary to go beyond the worst-case approach by using the statistical nature of the presence of co-channel interferences, as introduced in Equation (III-22).

The following section presents results for the joint coverage probabilities for typical EDGE layout and analyses the influence of network load (non worst case interferences), shadowing and sectorization.

III.3. Results for typical EDGE cellular

We seek here to specify the general expressions for a 2 and 3 BSs subsystem of III.2.1 under lognormal shadowing and sectorized layouts.

III.3.1. SIR probability density function

Further analysis of the SIR is needed here since we need in (III-3) the probability density function (pdf). From (III-1), the SIR received from BS 1 at the mobile at position (*x,y*) is:

$$\mathit{\Gamma}_1(x,y)=\left(\sum_{i=1}^{m_1}10^{w_i/10}\left(\frac{r(x,y)}{d_i(x,y)}\right)^{\gamma}\right)^{-1} \tag{III-26}$$

The SIR received at the same position from BSs 2 and 3 can be found from the same expression (III-26) with a different number of interferers and a shift in location coordinates. From Figure III-4 the shift in coordinates can be easily derived. For a two BSs subsystem, BS 2 system of coordinates (x_2, y_2) can be expressed as a function of (*x,y*): $(x_2, y_2)=(\sqrt{3}R-x, y)$. For a three BSs subsystem, the new coordinates in BS 2 and 3 systems of coordinates are (Fig. 6):

$$\begin{cases} x_2 = -(1/2)x-(\sqrt{3}/2)y+3R/2 \\ y_2 = -(\sqrt{3}/2)x+(1/2)y+\sqrt{3}R/2 \end{cases} \tag{III-27}$$

$$\begin{cases} x_3 = -(1/2)x + (\sqrt{3}/2)y + 3R/2 \\ y_3 = -(\sqrt{3}/2)x - (1/2)y + \sqrt{3}R/2 \end{cases} \tag{III-28}$$

There is clearly a need for the SIR pdf. The SIR pdf under lognormal shadowing and co-channel interferences cannot be expressed in closed form [43]. Several methods have been found to approximate it, most of them based on the fact that the sum of lognormal random variables could be approximated as a lognormal random variable [43]. For its simplicity, this work follows Wilkinson method [43] which approximates the sum of lognormal random variables by another lognormal random variable and matches the two first moments. Derivation of the moment matching in our case is given in Appendix B following the work done in [44] and under the assumption of shadowing independence as stated in section III.1.3. The $\Gamma_k(x,y)$ are therefore Gaussian in decibels with mean and variance:

$$\begin{cases} \mu_{M_k}(x,y) = (1/l)\left[l^2\sigma^2 + \ln\left(\dfrac{A_{M_k}(x,y)}{B_{M_k}(x,y)} \right) \right] \\ \sigma_{M_k}{}^2(x,y) = (1/l^2).\ln\left(\dfrac{\left(B_{M_k}(x,y)\right)^2}{A_{M_k}(x,y)} \right) \end{cases} \tag{III-29}$$

where $l = \ln(10)/10$ and σ^2 is the variance of w_i. A_{M_k} and B_{M_k} are found to be:

$$\begin{aligned} A_{M_k}(x,y) &= \left[\sum_{i=1}^{M_k} \left(\frac{r(x,y)}{d_i(x,y)} \right)^{\gamma} \right]^2 \\ B_{M_k}(x,y) &= \left[e^{2l^2\sigma^2} \sum_{i=1}^{M_k} \left(\frac{r(x,y)}{d_i(x,y)} \right)^{2\gamma} + 2 \sum_{i=1}^{M_k-1} \sum_{j=1}^{M_k} \left(\frac{r(x,y)^2}{d_i(x,y)d_j(x,y)} \right)^{2\gamma} \right]^{1/2} \end{aligned} \tag{III-30}$$

As the SIR is approximated to be normal in dB, the joint coverage probabilities (III-3) can be expressed as products of Q-functions:

$$P_{2\text{cov}|(x,y),(M_1,M_2)} = Q\left(\frac{z-\mu_{M_1}(x,y)}{\sigma_{M_1}(x,y)}\right).Q\left(\frac{z-\mu_{M_2}(x_2,y_2)}{\sigma_{M_2}(x_2,y_2)}\right) \quad \text{(III-31)}$$

$$P_{3\text{cov}|(x,y),(M_1,M_2,M_3)} = Q\left(\frac{z-\mu_{M_1}(x,y)}{\sigma_{M_1}(x,y)}\right).Q\left(\frac{z-\mu_{M_2}(x_2,y_2)}{\sigma_{M_2}(x_2,y_2)}\right).Q\left(\frac{z-\mu_{M_3}(x_3,y_3)}{\sigma_{M_3}(x_3,y_3)}\right) \quad \text{(III-32)}$$

Further evaluation of the expectation (III-4) and integral (III-6) are then straight-forward.

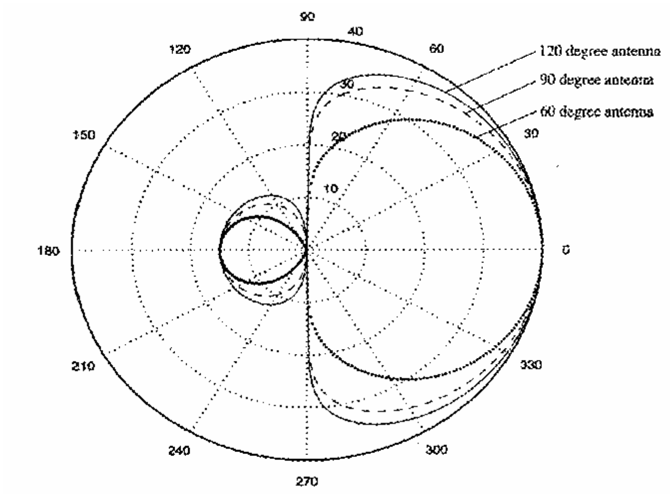

Figure III-8: sector antenna gains

III.3.2. Influence of load, shadowing and sectorization

Results for the joint coverage probabilities are provided for 1/7 with omni-directional antenna, 4/12 and 3/9 with 120^{o} antennas. The antenna gain was not included in the expressions in order to avoid surcharging them. Following [40], antenna gain from Figure III-8 was taken for the calculation in the 4/12 and 3/9 cases. Usual SIR analysis for 4/12 considers two full gain interferers at worst. However, this assumption becomes over-optimistic here since the mobile can be located out of its cell (See Figure III-9). Within a 2 or 3 BSs subsystem, the mobile can be located so that the two secondary interferers will have an angle to the mobile between 60 and 90 degree (Figure III-9) where the gain is still high. Therefore 4/12 is assumed to have at worst two full gain and two partial gain interferers due to non-perfect sector antenna. 3/9 was assumed to have at worst 3 full gain interferers since the two secondary interferers have an angle to the mobile greater than 90 degree where the gain is quasi null. The ranges of the number of interferers for each layout are then respectively $1 \le M \le 6$, $1 \le M \le 4$, and $1 \le M \le 3$. Path loss exponent is assumed to be 4 in this section, and shadowing intensity 6 *dB*.

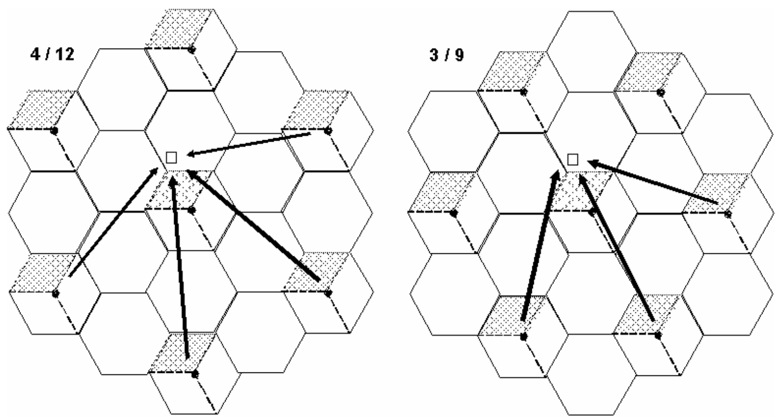

Figure III-9: 4/12 and 3/9 cellular layouts

Under the above mentioned conditions, these three layouts provide similar SIR at the edge of a cell. 3/9 and 4/12 provide better out-of-cell SIR since their co-channel interferers are situated behind the main direction of radiation of the sector. Therefore the interfering power decreases more quickly with distance to the BS than in 1/7 layout.

III.3.2.1. <u>Location based results</u>

The probability of being jointly served by several BSs depends very much on the location. In a deterministic SIR model such as in the previous section, a mobile is jointly covered if it is located around the middle of a subsystem, and is covered by one BS only if it is located near one BS. Introducing lognormal shadowing gives a non-zero probability to be jointly covered almost everywhere within the subsystem.

Joint coverage probability within a 2 and 3 BSs subsystem with respect to the location of the mobile is given in Figure III-10 and Figure III-10 from Equation (III-4) and (III-4). Layout 3/9 is taken and worst-case load is assumed. The requested threshold at the mobile from the BSs is set at 15 dB.

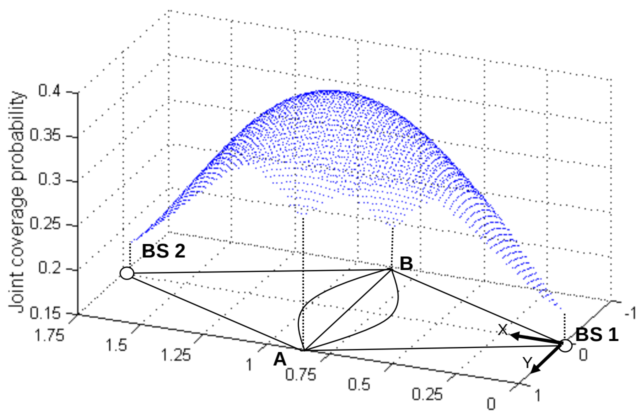

Figure III-10: joint coverage probability at the mobile for a 2 BSs subsystem with respect to the location

As expected, the probability of joint coverage is the highest in the middle of the subsystems, and the lowest when located near to a BS. Still, interestingly, the worst-case values in a 2 BSs subsystem when located near a BS are significant, being as much as 0.15. On the other hand, the worst-case value when located in the middle of the subsystem is less than 0.37. Lognormal shadowing indeed spreads the possibility over the whole area, but at the same time lowers the probability in the middle. It can be noticed that the spatial distribution is not symmetrical with respect to the x=0 axis for a 2 BSs subsystem. It is because in our model one side (point B) of the subsystem corresponds to the limit of the radiation area of the sector antennas of the two BSs, while the other side (point A) corresponds to the middle of the radiation patterns.

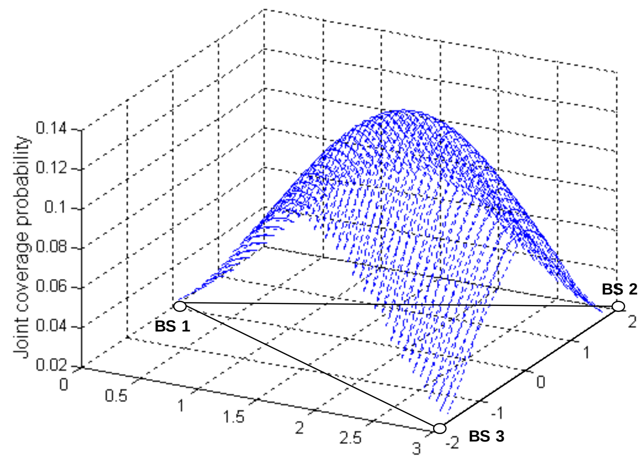

Figure III-11: joint coverage probability at the mobile for a 3 BSs subsystem with respect to the location

As seen in Figure III-10 the worst-case values in a 3 BSs subsystem are naturally lower. The probability of being jointly covered by 3 BSs is less than 0.14 in the middle and 0.01 when close to a BS.

III.3.2.2. Spatial average

As developed in section III.1.3, an interesting metric for quantifying the joint coverage at the mobile is the spatial average of the joint coverage probability from (III-4) and (III-4) using the joint coverage probabilities under log-normal shadowing (III-4) and (III-4). In this section, unless specified, the default values for the intensity of shadowing and the requested threshold at the mobile are 6 dB and 15 dB, respectively.

- Influence of shadowing

In Figure III-10 the spatial average of the joint coverage probability for a 2 BSs subsystem is plotted versus the one-path intensity of shadowing σ. Layouts 1/7, 4/12 and 3/9 are represented. Since shadowing decreases the mean SIR at the mobile, it expectedly decreases the joint coverage probability (slight increase for high shadowing values is due to Wilkinson approximation inaccuracy). It can be seen that the loss is roughly constant for the typical range of values of σ, that is 6 dB to 10 dB. *Compared to a non-shadowing model (σ = 0), the joint coverage probability is decreased by about 35%.*

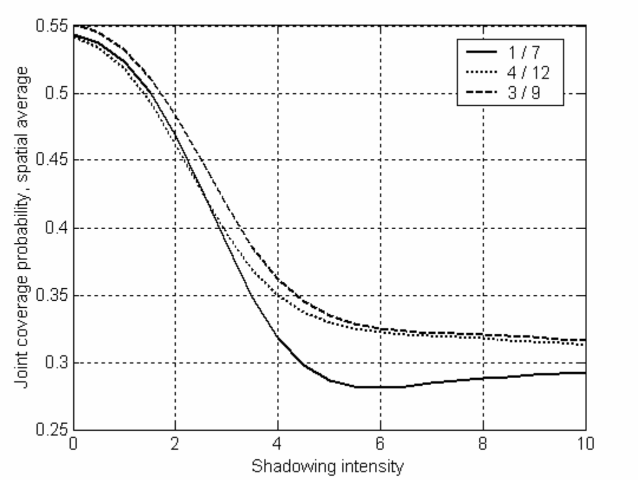

Figure III-12: Normalized joint coverage area for a 2 and 3 BSs subsystem with respect to the shadowing intensity.

In Figure III-13 and Figure III-13 the results for the different cellular layouts 1/7, 4/12 and 3/9 are shown for a 2 and 3 BSs subsystem. The spatial average is plotted versus the requested SIR at the mobile under two load situations: normal load and worst case conditions (*p*=1). For normal load, it is considered that the traffic parameter *p* is equal to 0.6 in all the interfering cells. This corresponds to a *GoS* of 1% for a 20 channels sector (as stated in the introduction, this is a reasonable dimensioning). **Simulation results are provided in Figure III-13 for validation of the analytical approach.**

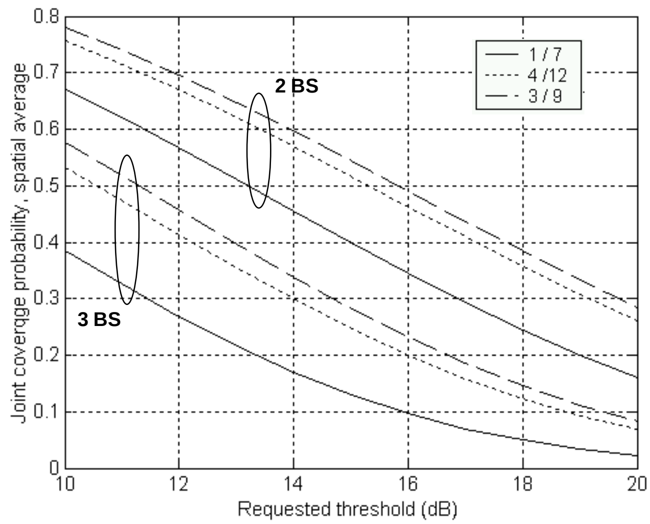

Figure III-13: Spatial average of the joint coverage probability: normal load

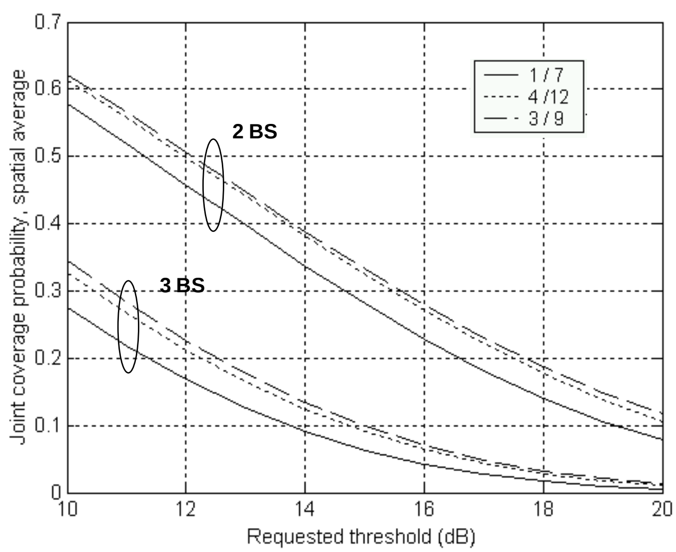

Figure III-14: Spatial average of the joint coverage probability: lower bound (permanent worst case load)

➢ Influence of sectorization

First, it can immediately be seen that sectorized layouts perform significantly better. As mentioned earlier, 3/9 and 4/12 provide better "out of cell" SIR than 1/7 and therefore give better joint coverage results. Second, this difference of performance compared to non-sectorized layouts is very dependant on the average network load. Under normal load, the difference between sectorized and non-sectorized is far greater than under worst-case load. It is understandable since sectorized layouts have fewer interferers and will therefore take greater advantage of a normal load situation. *The conclusion here is that tight 3/9 and 4/12 layouts, although similar to 1/7 from the provided SIR point of view, provide significantly better joint coverage than 1/7 and take better advantage of non worst-case load conditions*.

- <u>Influence of network load</u>

This study introduced in the results a network constant p quantifying the average traffic load. It aimed at being able of modulating the presence of co-channel interferers. Although worst-case interference assumption leads to lower bounds on the performance, we analyze here the joint coverage results under normal load situation as well. It should be clear what "normal load" means. It simply means that the number of channels in each cell is dimensioned according to the mean arrival rate and the mean service time in order to provide a certain GoS. As a result the average channel utilization p is not 1 and there is a high probability that a co-channel interferer is actually not active, resulting in less co-channel interferences and therefore better performance. Naturally, *temporary* light load or worst case load situations are taken into account in this approach. The point is that assuming *permanent* worst-case interference is very pessimistic.

From Figure III-13 and Figure III-13 it can be seen that the traffic assumption has a very important influence on the joint coverage results. *Assuming permanent worst-case conditions gives a safe lower bound, between 8% and 10% for 3 BSs and between 28% and 33% for 2 BSs . It means that on average, the probability for a mobile to be served jointly by 2 BSs in a 3/9 cellular system is necessarily more than 33%.* The "average" here refers to the spatial distribution. The significance of this worst-case figure is that from the traffic point of view, the situation cannot evolve towards worse interference conditions, resulting in a possible outage from one server. It means that the probability when connecting to the network to have 2 BSs is 33%, and the probability of being served continuously by these two servers without disturbance during the whole duration of service is 1, provided that the mobile is stationary.

However, worst case interference situation occurs with a probability 0.2 only (p to the power 3) in a 3/9 layout with traffic parameter p=0.6. *This highlights that most of the time, the probability of being jointly served by several BSs when connecting to the network is significantly higher*. From Figure III-13 and Figure III-13, it is on average between 15% and 30% for 3 BSs and between 40% and 55% for 3 BSs . "Average" refers here to one more randomness than previously, that is interferers' traffic randomness. This quantifies the fact that in most cases, the probability of being jointly served upon connection is significantly higher than the worst-case figures. However, it has to be kept in mind that the situation may evolve towards worse interferences conditions during the duration of service, resulting in a possible outage from one BS. The results given here are probabilities computed for a given time and do not guarantee that the value holds during a significant time lap. A more sophisticated traffic model would quantify more accurately the joint coverage problem under non worst-case conditions, giving results which would apply to the whole duration of service. Still our simple approach gives interesting results, but valid upon connection only.

III.4. Summary and discussion

This chapter establishes an analytical framework for joint coverage problems in single-layered cellular networks. A convenient analytical approximation for the normalized joint coverage under simple log-distance model, worst-case co-channel interferences and symmetrical layout was derived based on the work done in [31]. It is aimed at quick evaluation of feasibility. Results were then developed for typical sectorized EDGE layout. We analyzed the influence of cellular, channel and network parameters on this scheme. Tight typical sectorized layouts are found to perform better than equivalent (from the provided-SIR point of view) non-sectorized layouts. Network load is shown to have a very significant impact on the joint coverage probability especially for sectorized layouts: normal load conditions enhance the feasibility significantly. The joint coverage probability depends very much on the mobile's location. Expectedly, in a LOS model, the mobile can be jointly covered only when located near the middle of the subsystem. Introducing realistic channel conditions with log-normal shadowing showed that the joint coverage probability can be significant even when located close to a BS. This fact is very interesting for the proposed load-sharing scheme.

It is shown that within the same layer of cells under quite general circumstances for channel and network conditions, the probability that the mobile can be served by 2 or 3 base-stations is very high in a typical dense EDGE like network. The important figures are summarized in Table III-1.

	Normal load		Lower bound	
	2 BS	3 BS	2 BS	3 BS
1 / 7	*40%*	*13%*	*28%*	*7%*
4 / 12	*52%*	*26%*	*32%*	*10%*
3 / 9	***55%***	***29%***	***33%***	***11%***

Table III-1: Joint coverage probability, spatial average

Several important factors must be mentioned concerning the previous analysis. As far as worst-case conditions are concerned, it is important to note that they are really worst-case:

- The usual hexagonal model employed and reality can be very different. Usually operators' frequency planning carries a margin. It is very difficult to find some available commercial data about coverage. We studied the CNET GSM commercial benchmark [45] made in 1998 in south of France over an entire region including cities, thanks to France Telecom. 30000 points of measures with the received signal from all the surrounding base-stations are available along with the location of the base-stations and a proposed frequency planning. It is therefore possible to establish a statistical figure on the proportion of the area where more than 2 BS give a signal with good SIR. We found that an overwhelming proportion of the area had indeed more than 2 BSs coverage. It is not reported here since we are not sure whether the frequency planning given is efficient.

Moreover this was during the early days of GSM where the number of subscribers was rather low and therefore operators could afford loose planning. However this suggests that the real implementation of cellular networks results probably in a significantly better coverage than the theory would suggest it.

- As mentioned earlier, the figures given do not include umbrella cells coverage, or other operators' cells.
- Power control was not taken into account in our analysis. This means that we assumed that when an interferer was active the BS would emit full power. It is a worst case hypothesis since in a lot of cases the interferers may not need full power.

Consequently we can be confident in the worst-case figures we have developed. However, concerning the approach taken to account for non worst-case network load, several points need to be mentioned, as stated earlier:

- The worst case figures given are a lower bound which can be considered at any time for any user. However, the non worst case load figures are statistical expectations (with respect to the instantaneous loads of interfering cells). It implies that the real figure available at the user can be higher or lower.
- The non worst-case figures given are *instantaneous* probabilities. That means that at any given time for a new user, its average probability to receive correctly from 2 or 3 base-station is $P_{2\text{cov}}$ or $P_{3\text{cov}}$. However, this does not mean that this statement will remain true during the whole duration of the connection. It is likely that the interference situation will evolve to a better or worse situation. The normal load analysis is carried out to show that due to the dynamic traffic, the

joint coverage situation is very often far better than worst-case, especially with tight sectorized cellular layouts.

- If using this scheme a user is connected to a remote BS during a light interference situation and suddenly the interferences increase the following scenarios can happen. Usually the user asks its serving BS to increase its transmitting power to keep signal integrity. If the BS has reached its maximal transmitting power, the user is dropped (GSM) or uses a modulation and coding scheme able to cope with a lower SIR (EDGE). Since we consider the study in an EDGE context, we can assume that the user will be able to cope with the temporary high interference situation.

In conclusion, we can expect a mobile user within a typical EDGE cellular network to be adequately covered by at least 2 BSs. As its feasibility is now quantified, it is possible to carry out the design and performance of the super-users class accommodation scheme.

CHAPTER IV DESIGN AND PERFORMANCE OF DATA-SPLITTING RESOURCE ALLOCATION SCHEMES FOR MULTIPLE CHANNELS DATA SERVICES

The main design challenge is to find a resource allocation algorithm that allows a super user to aggregate a significant amount of bandwidth while minimizing the impact on the system. It was proposed as a principle to use several base-stations in order to optimize resource allocation thereby achieving load-sharing. We do not address here the architectural and technical implementation of multiple BSs service (signaling, DLL bundling, handovers…) but rather focus on resource allocation algorithms and their performance.

This chapter is organized as follow: in a first part we develop simple analytical traffic analysis for simple resource allocation schemes based on the joint coverage results, which allow a quick traffic gain derivation. Simulations are then carried out. In a second part the simulation test bed is described. Then different resource allocation algorithms are analyzed for EDGE systems under the hypothesis of Circuit Switched Data (CSD) using simulations. This assumption was taken since a super-user might need non-bursty traffic such as downloads and streaming. From another point of view, a mobile hot-spot aggregates the traffic of several users and therefore is more likely to need real circuit-switched channels. In any case, if the super user uses very bursty traffic, the proposed idea might not be necessary, since statistical multiplexing can be efficiently done with E-GPRS. However, the concepts used can be applied as well to optimization of packet-switched mechanism. The gain would be the same.

IV.1. Analytical load-sharing gain

As reviewed in Section II.2, a few papers have considered the load-sharing gain for voice traffic. We develop here some simple results for multi-channels data traffic. For voice traffic, load-sharing is achieved by selecting another BS if possible according to the respective load situations. We therefore call it "BS selection" load-sharing. For data services, since in most case the user will need several slots, several BSs can serve simultaneously the mobile. We call it "multiple base-stations" load-sharing.

IV.1.1. Assumptions

For simplicity it is assumed in this section that the load-sharing schemes make use of 2 BSs only. In other words, the context of the following is a two base-station subsystem, as shown in Figure IV-1. Results can be extended to 3 BSs in a straightforward manner.

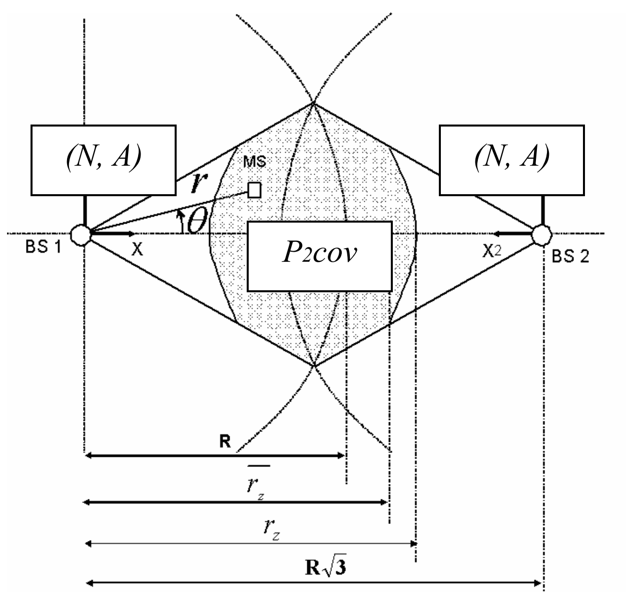

Figure IV-1: BS subsystem for traffic analysis

The system is defined as follows:

- BS 1 and 2 of the subsystem have each N channels for their respective facing half-sectors and accommodate traffic intensity A (symmetric load).
- Here a simplification is made. Strictly speaking, the reference layout is 3/9, that is with 120 degree sectors. The two facing sectors of the 2 BSs subsystem are 60 degree. We will assume that half of the resources of the sector are given to the 60 degrees sector. This is required to make the analysis simple, but is not strictly accurate.
- The system is assumed to be a simple Erlang system: service time is exponentially distributed and arrivals follow a Poisson process. There is no queuing of requests.
- The mobile is in the joint coverage area with probability $P_{2\text{cov}}$, and in the other area with probability $(1 - P_{2\text{cov}})$.
- The joint coverage results developed in the previous chapter are used. We will take the following approach. As stated earlier, the joint coverage figures under normal load are valid upon connection only. It is therefore risky to use them as constant parameters for the traffic analysis. Lower bound figures are safe to use but are inherently pessimistic. *We will therefore take as a reference figure slightly more than the lower bound figure, that is a 2 BSs joint coverage of 40% in a 3/9 EDGE layout*.

IV.1.2. BS selection load sharing: voice traffic gain

➢ <u>Analytical derivation of traffic gain</u>

The blocking probability for the mobile without sharing is obtained with the Erlang B formula:

$$P(N,A)=\frac{A^N/N!}{\sum A^k/k!} \quad \text{(IV-1)}$$

Past work on load-sharing describes analytical figures for a well defined sharing strategy, which makes the analysis quite complex. In [14][16] the Markov chains are re-built from scratch with new flows depending on the strategy. Direct retry and a more complex strategy of guard channels and global balancing are analyzed this way, which proved to be fairly complex. In [15], a global approach based on calculated overflows is taken. However strategies of overflow accommodation are non optimal. Moreover it seems that the analytical results vaguely match the simulation results. The interest of these analyses is that they are strategy specific and allow more flexibility on parameters (asymmetric systems e.g.). Keeping in mind that our analysis is targeted at multi-channel data-users, a very simple but accurate approach is needed. An approach based on average figures which can be applied for both voice and data traffic is described in this chapter. However, this approach holds for symmetric load only and is independent of the strategy chosen.

The idea behind is the following. For a non sharing system, there is an offered load of A and each user is in a system of N channels. Knowing these parameters, the blocking probability $P(N,A)$ can be computed from (IV-1).

Assuming a complete sharing system (each user can see two N channels systems, or $P_{2\text{cov}}$ =1), and considering the two sectors as one global system, we have a trunking system of $2N$ channels with an offered load of $2A$. The blocking probability

$P(2N,2A)$ can be computed from (IV-1) as well (and will be lower than $P(N,A)$ of course). This is stated in [15] for example.

Our system is a partial spatial sharing, so it is, *on average,* something in between these two figures. Considering the two sectors as one global system again, we can say that on average one user "sees" *N* channels with probability $(1-P_{2\text{cov}})$ and *2N* channels with probability $P_{2\text{cov}}$. Therefore the average number of channels available to the user is $(1+P_{2\text{cov}})N$. Similarly from this average pool of channels point of view, the offered load to them is *A* with probability $(1-P_{2\text{cov}})$ and *2A* with probability $P_{2\text{cov}}$. Therefore the average offered load for this system is $(1+P_{2\text{cov}})A$. We can then compute the average blocking probability considering the two sectors as an Erlang trunking system with $(1+P_{2\text{cov}})N$ channels and an offered load of $(1+P_{2\text{cov}})A$ using (IV-1).

➢ <u>Validation and comments</u>

It should be clear now why this approach is valid for symmetric load only and independent of the sharing strategy. In a way it assumes that on average a bigger pool of channels is available for every user, and that there are more users on the system. That implies that it should give results corresponding to an optimized sharing strategy, i.e allowing even for non-shared user to be served correctly. To this extent we expect this approach to give a lower bound on the average blocking probability. An obvious problem occurs when the average number of channels is non integer, since (IV-1) holds only for integer values of *N.* The approach taken was to calculate the blocking probabilities for a given offered load and an extensive range of values of *N*. Then the result for a non integer value would be obtained by accurate interpolation of the previous figures.

Although voice sharing is not our main concern here, we validate the previous approach with some simulation results. The simulation test-bed is described in detail in the next section. The following sharing strategies can be used:

- Handling of the overflow when possible (best effort) [15]. A user in the overlapping area tries to be served by its main server. If the latter is congested, it tries to be served by the other BS. It improves the performances but it is not very efficient. Moreover, users who can be served only by their BS are disadvantaged in this scheme (since the channel utilization will increase, the probability for this kind of users to be blocked will be higher compared to a normal system).
- Handling of the overflow with guard channels reserved for own-sector users who wouldn't be able to receive from more than one server [14]. This reestablishes fairness among the users compared to the previous strategy.
- Global sharing [16]: the system can decide to hand-over existing user to neighbor cells in order to accommodate other overflowed neighbor cells users. This method is efficient but somehow very complex to implement. It has to be noted that our analytical approach is valid for sharing strategy involving the two facing sectors only. Therefore we cannot compare its results with those of a global load-sharing strategy, which would involve more parameters.
- We propose here a natural local balancing method. This method is well known in packet scheduling systems. It aims is to balance the load, i.e. to minimize locally the loading difference between neighbours with any new arrival. Concretely a

new user being in the overlapping area would be served by the less loaded server among the available servers. This constantly tries to avoid congestion in all the servers. It is more efficient than overflow handling system since it constantly tries to balance the load. We will analyze in more detail these strategies with data users.

The analytical results based on our simple approach are plotted in Figure IV-2. We calculate the values of $P(N, A)$ -normal system (no-sharing), $P(2N, 2A)$ -ideal full overlapping system, and $P[(1+P_{2\mathrm{cov}})N, (1+P_{2\mathrm{cov}})A]$ -realistic partial overlapping system. The results from simulations are also plotted for two sharing strategies: best effort overflow handling and load minimization. The simulation parameters are given in Table IV-1.

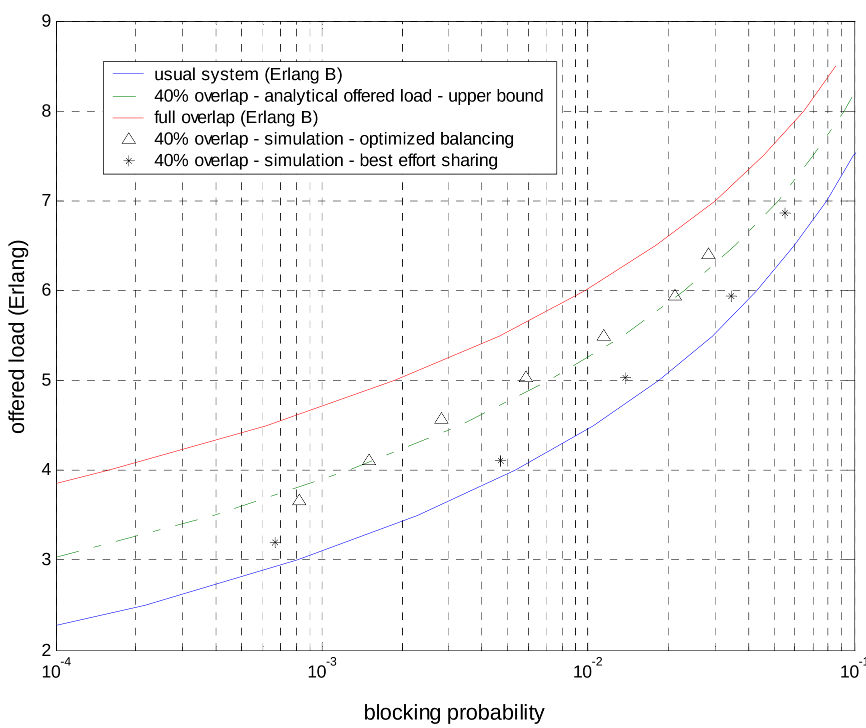

Figure IV-2: offered load versus blocking probability in a 2 BSs subsystem

Total number of slots / sector	10
Voice users service time	2 min
Voice users arrival rates (/hour)	123, 137, 150, …
Simulation "real" duration /point	6.6 hours
Cellular Layout	3/9 frequency planning
Power control	No
Shadowing intensity	6 dB
Co-channel interferences	Worst-case
SIR requirement (GSM)	15 dB

Table IV-1: simulation parameters for voice traffic

First of all it can be seen that our simple approach seems coherent. For a joint coverage probability of 0.4, the offered load for a given blocking probability is between the ideal load given by a full overlapping system, and the load given by a non-overlapping system. It can be seen as well that the analytical result seems to give an upper bound on the performance of the load-sharing system. The best-effort method performs poorly and is way below the analytical result. The load minimization strategy, which gives the best results for a local sharing strategy, matches closely with the analytical results.

This shows that this inexpensive analytical approach gives good results and can be used as an upper figure. With this knowledge, we can exploit the analytical results to derive traffic gains, and extend the analysis to multi-slot data users.

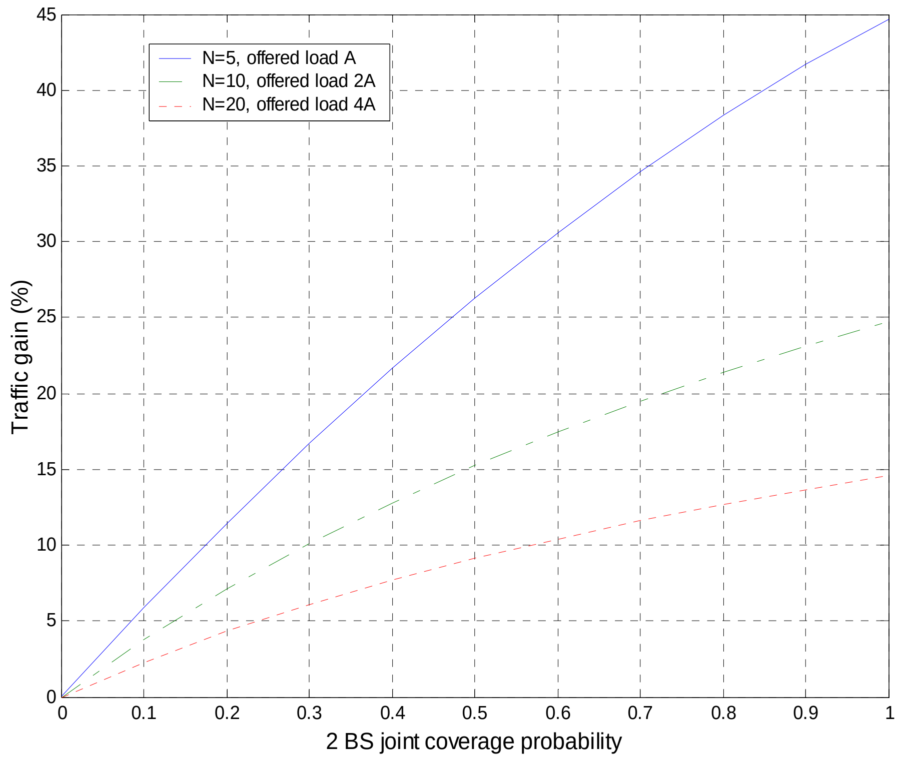

Figure IV-3: voice load-sharing traffic gain

In Figure IV-3 the analytical traffic gain of voice load-sharing is plotted. The gain is obtained the following way. For a range of relevant blocking probability and a given joint coverage probability, the offered load is computed and the mean gain versus a normal system's offered load is computed. Several trunking conditions are analyzed to see the influence of the system size on the gain. By size we mean the number of channels and corresponding offer load.

As expected the gain increases with the joint coverage probability. It can be seen that the gain varies very significantly with the system size. A small trunking system, i.e with a limited number of channels and an accordingly small offered load will take significant advantage of a load-sharing scheme. On the contrary a big trunking system with an accordingly big offered load will not take much advantage of a load-sharing scheme. This fact will be crucial when dealing with multi-slot class systems.

The purpose of this part was to introduce and validate a simple analytical approach for traffic gain derivation. We now extend this approach for multi-channel data users.

IV.1.3. Multiple BSs load-sharing: simplified analysis

It was stated earlier that intuitively it seemed more interesting to use load-sharing and splitting for super-users using bandwidth aggregation methods. We investigate here the traffic gain for a simple system with a class of heavy users. Introduction of adaptive modulation and coding (MCS in EDGE) and / or QoS greatly increase the complexity of the analysis. Such advanced cases will be studied though simulation in the next part. Packet-switched systems are in themselves more efficient for a category of data traffic, but there is no reason why the gain of load-sharing would be greater for packet-switched systems than for circuit-switched systems. We focus here on simple results and hence analyze the theoretical efficiency of the proposed scheme on circuit-switched systems. We take a simple Circuit-Switched Data (CSD) system on top of the voice system. Voice and data users are considered for simplicity at the same level of priority.

➢ Analytical results for normal multi-slot CSD

The general assumptions taken have been specified at the beginning of this section. The analytical framework for a normal trunking system with different multi-slots classes' k is well known. The equilibrium steady-state probabilities are given by the Kaufman-Roberts recursion:

$$\pi(l) = \frac{\rho_{\text{voice}}}{l}\,\pi(l-1) + \sum_{k=1}^{K} \frac{k\ \rho_{\text{data,k}}}{l}\,\pi(l-k) \qquad \text{(IV-2)}$$

where ρ_{voice} is the offered load for voice, $\rho_{data,k}$ is the offered load for multi-slot k users and $\pi(l)$ is the probability that l slots are being occupied, with $1 \le l \le N$. $\pi(0)$ is chosen so that the sum of the steady-state probabilities is one. The blocking probability for multi-slot k users is then naturally given by:

$$P(k, N, \rho_{\text{voice}}, \rho_{\text{data,1}}, ..., \rho_{\text{data,K}}) = \sum_{l=N-k+1}^{N} \pi(l) \qquad \text{(IV-3)}$$

➢ Differences and similarities with voice traffic

It has to be understood first that a pure voice system with N channels and an offered load of A is strictly equivalent from the trunking point of view to a pure CSD system with multi-slot class 2, $2N$ channels, and offered load A. The following major facts will make the results on CSD more interesting:

- CSD and voice are usually mixed on the same pool. Given the dynamic traffic, a low traffic period for voice will definitely enhance the performance for the CSD users. In other words, different classes of traffic will take advantage of each other's dynamic occupation of the resources.
- CSD users are very resource consuming. Therefore, naturally, or rather structurally the amount of resources affected to be able to cope with them will be important even for a small CSD offered load. Let's give a concrete example. Assume that the voice load A roughly requires 10 slots. To accommodate a CSD class 2 load of intensity $A/2$ will also require 10 slots. This shows that in most

cases the high classes' loads will be structurally lower than voice loads. It's simply a matter of availability of radio resources. Operators usually do not have enough capacity to accommodate important loads of high class users (provided they exist…), therefore the amount of resources affected to them will not be very important. And given that they require more resources per user, the offered load which can be accommodated will be rather low.

- Let us follow our simple example. We assume then that the operator has doubled the capacity of each cell to accommodate class 2 CSD users. 20 channels are therefore available. The offered load mentioned are rough estimates since as we mentioned the different classes of users take advantage of each others resources. (same pool, so in fact it has to be more, the operator will accommodate slightly more than *A* for voice, and slightly more than *A/2* for CSD users). Now, 10 channels with an offered load of *A/2* of CSD class 2 users is strictly equivalent from the trunking point of view to 5 channels with an offered load of *A/2* of voice users. We recall from Figure IV-3 in the previous part that load-sharing will be far more interesting for smaller size systems. It applies here exactly. That means that applying the strategy for the CSD class 2 users in our 20 channels systems will lead to a greater gain for them than for voice users. *We can then conclude that, since structurally high CSD classes of users will constitute smaller "systems / offered load" (since they are expensive in resources), the interest in using load-sharing / data splitting for high class of users is definitely more interesting than for voice users or low class data users.*

We summarize the previous reasoning:

- fact 1: different classes of users can make use of each other's resources.
- fact 2: structurally the higher the class is, the lower the offered load will be (most probably, from an operator point of view)
- fact 3: as a consequence of fact 2, the higher the class is, the higher the load-sharing gain is.

➢ Analytical results for CSD/voice load-sharing

We will use here the same approach as with voice systems for traffic performance analysis. Using the Kaufman-Roberts recursion, the blocking probabilities for the different classes of users can be computed using (IV-3) with the following parameters:

- $P(k, N, \rho_{\text{voice}}, \rho_{\text{data,1}}, ..., \rho_{\text{data,K}})$ for a normal system.
- $P\lfloor k, (1+P_{2\text{cov}})N, (1+P_{2\text{cov}})\rho_{\text{voice}}, (1+P_{2\text{cov}})\rho_{\text{data,1}}, ..., (1+P_{2\text{cov}})\rho_{\text{data,K}} \rfloor$ for a realistic 2 BSs overlapping load-sharing system. If it leads to non integer values of the number of channels, interpolation will be used.
- $P(k, 2N, 2\rho_{\text{voice}}, 2\rho_{\text{data,1}}, ..., 2\rho_{\text{data,K}})$ as a reference for a full ideal overlapping system.

To validate the previous reasoning we consider the following examples. First the results for middle class data users are developed (CSD class 3). Then we take a more "super user" point of view with a small CSD class 7 group of users mixed with voice.

CASE STUDY 1:

- 10 channels are available.
- The traffic is mainly voice with offered load ρ_{voice}.

- CSD class 3 offered load of $\rho_{\text{data},3}$ (roughly $\rho_{\text{voice}}/3$). The same SIR threshold is requested.

CASE STUDY 2:

- 15 channels are available.
- The traffic is mainly voice with offered load ρ_{voice}.
- CSD class 7 offered load of $\rho_{\text{data},7}$ (roughly $\rho_{\text{voice}}/7$). The same SIR threshold is requested.

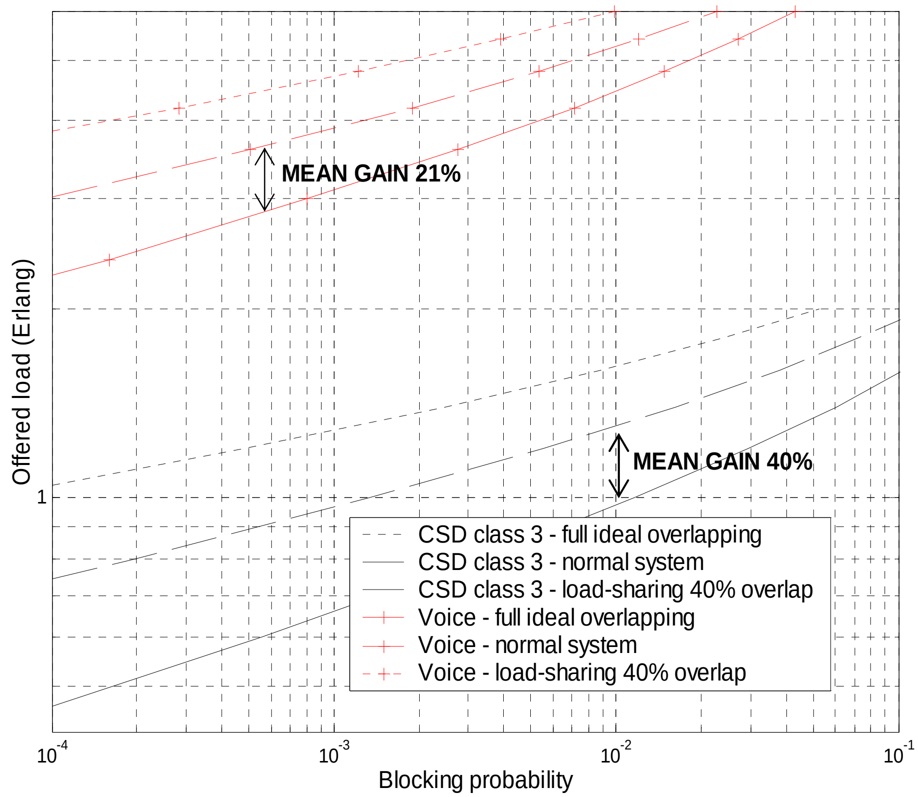

Figure IV-4: offered load versus blocking probability for mixed voice and data CSD class 3 traffic (10 channels).

The traffic is mixed without specific priorities within the different classes. Once again it should be emphasized that the results are independent of the sharing strategy used and assume optimized sharing. This has more important implications for data users since it means that their slots may need to be allocated simultaneously to the two BSs for best balancing (data splitting). The next part will focus more precisely on the multi-slot allocation strategy.

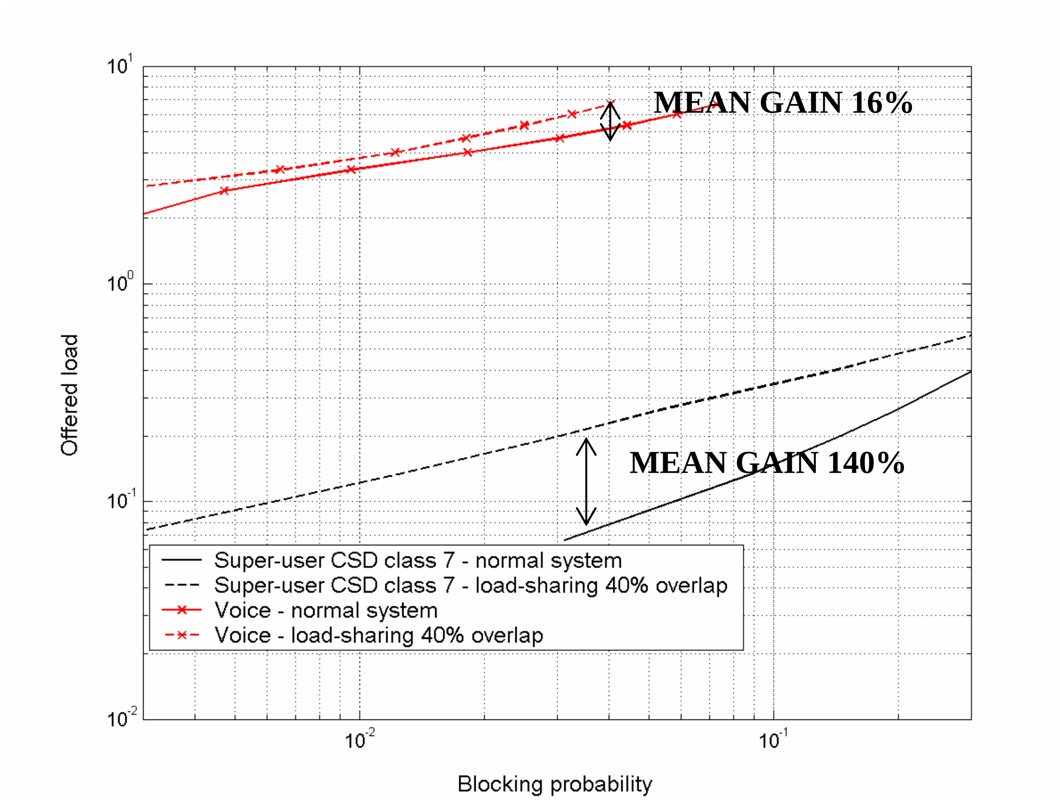

Figure IV-5: offered load versus blocking probability for mixed voice and super-users data CSD class 7 traffic (15 channels).

The analytical results based on our simple approach are plotted in Figure IV-4 and Figure IV-5. They confirm the fact that the gain is significantly higher for CSD users than for voice users. Typically voice users experience a mean gain of 15% (15 channels system) to 20% (10 channels system). Middle class data users experience a mean gain of 40%

with load-sharing while CSD class 7 super-users capacity is enhanced by 140%. This means concretely that for a blocking probability of 0.1 and a service time of 2 minutes, a normal system can accommodate 4.3 super-users per hour (with the dimensioning given above) while a 2 BSs sharing system can accommodate 10.4 super-users per hour within the same resources. Taking into account a third BS for sharing and/or umbrella and other operator cells would further enhance the capacity and allow a significant number of super-users to be accommodated within the same resources. This can be shown using the same reasoning with $P(k, \alpha.N, \alpha.\rho_{\text{voice}}, \alpha.\rho_{\text{data,1}},..., \alpha.\rho_{\text{data,K}})$ from (IV-3) where α would be larger than 2 (assuming 3 BSs sharing with one umbrella cell, it would be around 3). However it leads to high values of the number of channels which make the recursion (IV-2) extremely lengthy to be solved (the computing time increases dramatically with the cardinality of the recursion).

As stated before the gains depend as well on the global size of the system. As mentioned in the introduction, the sizing taken here is reasonable for dense urban sectorized system (8 to 24 channels per sector, or 4 to 12 per half-sector). That makes once again the proposed scheme a good idea for tight dense urban cellular systems. Analysis for higher super-users classes can be done similarly.

The aim of this part was to provide simple tools for traffic gain evaluation of multiple base-stations load-sharing for data users. The analytical approach was validated with simulations on voice systems and was found to give an upper bound on the real figure. The traffic gain is obviously an increasing function of the joint coverage probability. The traffic gain of load-sharing depends heavily on the system size. As a consequence it was stated that the gain is higher for high class CSD user than for voice users. A first case study showed that the gain for CSD class 3 users is twice that of the gain of voice users. Typically the gain is 40% in offered traffic for a small class of CSD class 3 users in a scenario with 10 channels available per half-sector (realistic). The second case study showed that a 2 BSs load-sharing system can accommodate 1.5 times more CSD class 7 super-users than a normal system (gain is 140%). This shows that the interest of applying the proposed scheme might be a luxury for voice users but become a definite requirement for super-users integration, especially when the corresponding population is small.

As mentioned in this part, the analytical results are independent of the sharing strategy and cannot be applied to systems with adaptive modulation and coding. Concrete implementation of the sharing algorithms for super-users over EDGE systems needs to be analyzed. This is carried out in the next part via simulations.

IV.2. Simulator specifications

We first investigated the possible use of existing simulators such as NS-2, OPNET or GPRSim. It was found that modifying them for a serious physical layer support and multiple base-stations operations would be much of a challenge. It was therefore decided to implement a Layer 1 / Layer 2 GSM/EDGE synchronous simulator using Matlab.

IV.2.1. Simulator structure

The basic element of the simulator is the GSM frame unit. The simulator performs allocations/releases/checks every frame time. Delay due to channel access, authentication, and signaling is not strictly taken into account since it would not affect the results. Figure IV-6 gives an example of the simulator tasks for one GSM carrier.

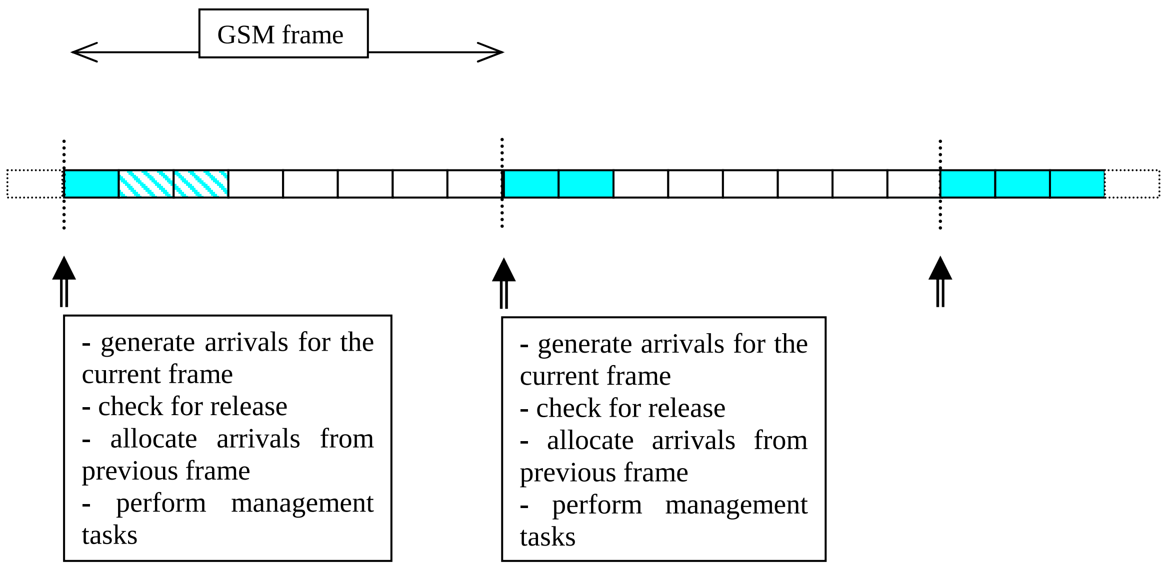

Figure IV-6: simulation of radio access for one GSM carrier

IV.2.2. Physical layer

As far as voice users are concerned, we assume that the radio conditions are good enough to make a GSM call. Therefore we do not implement physical layer functions for voice users. Voice traffic is just implemented to create a realistic dynamic resource occupation.

For data users, physical layer operations are implemented as follows:

- Location is randomly generated within the subsystem. In first approximation, the mobile is supposed to be static during the call.
- Based on this location, the SIR from the 3 BSs at the mobile is calculated following the assumptions of section III.1 that is for a path loss exponent of 4, 3/9 sectorized layout, and worst case co-channel interferences. We add randomly generated lognormal components to account for shadowing.
- Based on these SIR, we determine the Modulation and Coding Scheme (MCS) of EDGE the mobile can get from the different BSs (which eventually determines the data rate per slot). For simplification, we take only 3 MCS, as shown in Table IV-2. The minimum SIR required to achieve the given throughput at an arbitrary low Block Error Rate (BLER) is obtained from [46] in Figure IV-7.

Scheme	Data rate (Kbps)	Required SIR (dB)	Modulation	Code rate
MCS-2	11.2	> 10 dB	GMSK	0.66
MCS-5	22.4	> 17.5 dB	8-PSK	0.37
MCS-7	44.8	> 25 dB	8-PSK	0.76

Table IV-2: simplified MCS specifications

- Strictly speaking the throughput given here does not account for radio BLER. A table with BLER versus SIR would be needed when dealing more specifically with packets to account for retransmission. It has to be noted as well that throughput given here is a “user” throughput per slot, but includes the capacity needed for RLC / SNDCP / TCP / IP overheads. The real user throughput would therefore be slightly lower.

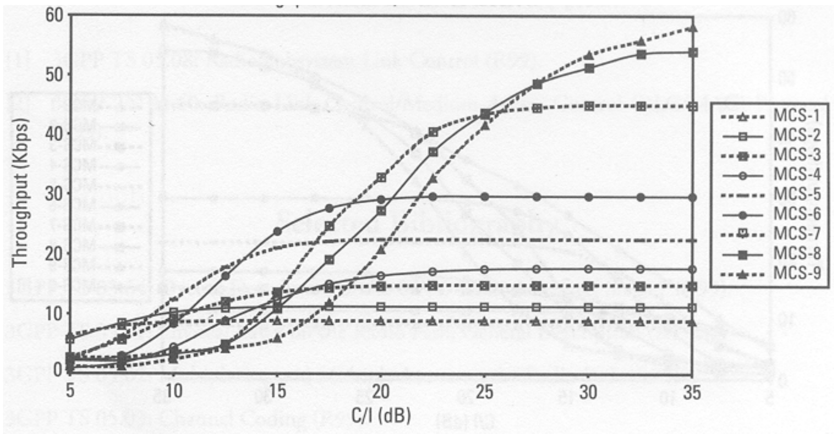

Figure IV-7: MCS throughput versus SIR (ETSI typical urban 3)

IV.2.3. Resources management

To accommodate voice and data traffic, the resources are shared according to the double boundary principle with voice non-preemptive priority, as shown in Figure IV-8.

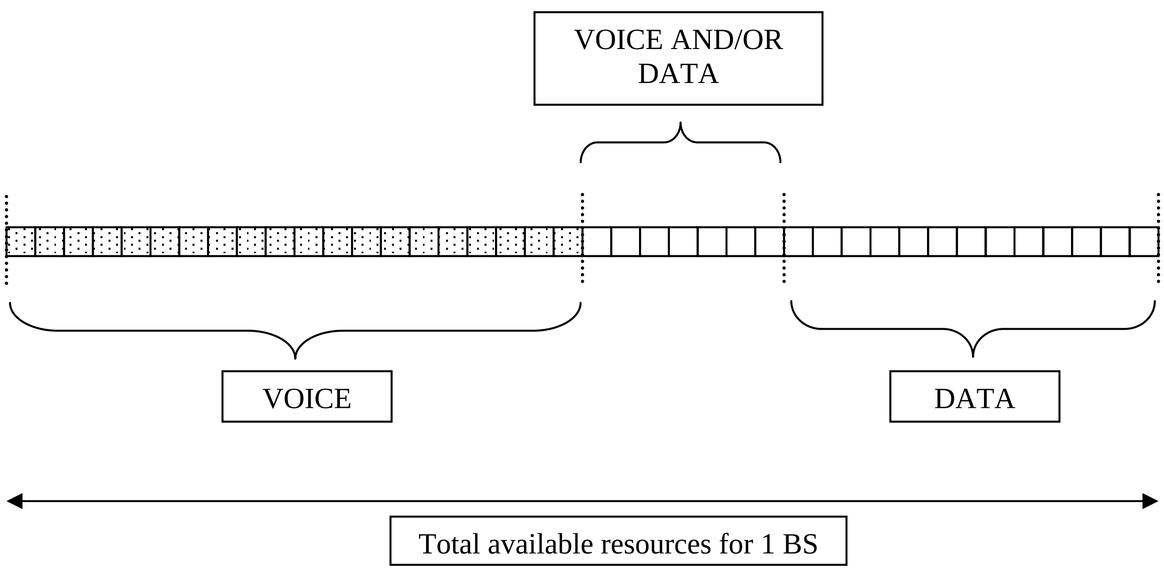

Figure IV-8: sharing of resources between voice and data traffic

The principles are the following. Within the voice part, only voice users can be allocated. Within the data part, only data users can be allocated. Within the middle window, data users can be allocated only if the data part is saturated and the voice part is not saturated (voice has then priority for the middle window). That means that if the voice traffic is high, only voice users can make use of the middle window. If some data users are accommodated in the middle window, and if the voice part reaches saturation, voice users can be allocated within the middle window if there is space. However, they cannot force the data users already being serviced to be terminated (non preemptive). Depending on the size of the middle window, this scheme allows data users to take advantage of more resources if voice traffic is low. This is of crucial importance for a load-sharing scheme: this creates potentially a lot of resources which can help to prevent / accommodate congestions. The above described scheme is fully implemented in the simulator.

IV.2.4. Traffic assumptions

- <u>Voice traffic</u>

Arrivals are randomly generated following a Poisson distribution with mean λ_v. In the simulator, at the beginning of each frame, the number of arrival for the current frame is generated with a Poisson random variable of mean $\lambda_v \times \text{frame duration}$. (This mechanism creates a valid random Poisson process since it's a memory-less process). Upon arrival, the service time is randomly generated following an exponential distribution of mean $1/\mu_{\text{v}}$. The offered load $\lambda_v / \mu_{\text{v}}$ is scaled to achieve a given GoS within the available voice resources.

- <u>Data traffic</u>

We assume non-bursty traffic, typically FTP downloads. As mentioned earlier a circuit-switched strategy is chosen, using E-CSD. To investigate the load-sharing strategies two mechanisms are analyzed: middle class data users with a fixed rate (44 Kbps or 90 Kbps) service, and a small super-users class with a fixed number of slots (10). This is an interesting case since depending on the location/radio conditions a fixed rate user requires a different number of slots. On the contrary, fixed multi-slot user experiences different throughputs. Arrivals are generated following a Poisson process and service time is assumed to be exponentially distributed.

IV.3. Design and performance of load-sharing schemes

IV.3.1. Middle class data users with fixed rate E-CSD

Since the scenario investigated is static for the moment, the criterion for BS selections will be SIR based rather than location based. Indeed the random lognormal component will often create situations whereby the closest server is not the best SIR server. Only with mobility it makes sense to take into account the current location / direction for a more efficient resource allocation scheme. To design a resource allocation scheme, two problems need to be solved. First, given a set of available servers, a decision has to be made, depending on their respective loads, whether to use them or not. Second, given an available server and an MCS scheme, the number of slots to be used from this server has to be determined. We assume in this section a 3 BSs subsystem.

The leading principle is that the allocation should try to distribute the number of slot needed among the available servers. However, respective loads have to be taken into consideration, as well as the absolute number of slot needed corresponding to the decision. Table IV-3 shows the number of slot needed to achieve the fixed rate depending on the MCS available from the different servers.

MCS-7 slots	MCS-5 slots	MCS-2 slots	Total num of slots	Data rate
1	0	0	**1**	44 kbps
0	2	0	**2**	44 kbps
0	1	2	**3**	44 kbps
0	0	4	**4**	44 kbps
2	0	0	**2**	90 kbps
1	2	0	**3**	90 kbps
0	4	0	**4**	90 kbps
0	3	2	**5**	90 kbps
0	2	4	**6**	90 kbps
0	1	6	**7**	90 kbps
0	0	8	**8**	90 kbps

Table IV-3: number of slot needed to achieve a fixed data rate depending on the available MCS.

Here follows two typical scenarios to avoid:

- Distributing the capacity leading to a worse situation. Let's assume BS1 and BS2 can be reached with both MCS-5 conditions. Let's assume that we need a fixed rate of 90 Kbps. We therefore need 4 MCS-5 slots. The following options are here possible: take 4 slots from BS1, take 4 slots from BS2, or distribute 1/3, 2/2, or 3/1 between BS1 and BS2. Let's assume the BSs are loaded as shown in Figure IV-9 on the left. A blind sharing would typically allocate two slots on BS1 and two slots on BS2, which leads to the load on the right of Figure IV-9. This situation is worse than without sharing since BS2 is now close to saturation.

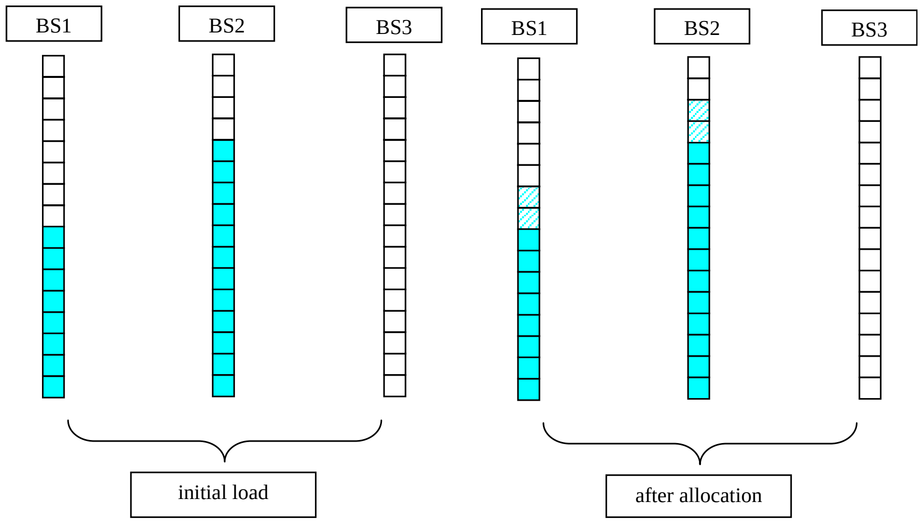

Figure IV-9: example of scenario.

• A second scenario to avoid is distributing the capacity when it seems really needed while the new number of required slots due to the distribution is significantly higher than without sharing. As seen in Table IV-3, assuming one MCS-5 server and one MCS-2 server are available to the user, depending on the distribution decision, the user will occupy from 4 to 8 slots for the same service. There is a fundamental tradeoff to consider when several servers are available but with different MCS: load balancing versus absolute amount of resources needed. The example shown in Figure IV-10 illustrates this problem. We assume BS1 is available with MCS-2 and BS-2 available with MCS-5. Given the initial load, it seems appropriate from a balancing point of view to try to get everything from BS1 rather than BS2. However doing so would require 8 slots since from BS1 only MCS-2 is available. This would indeed balance the load but artificially increase the amount of reserved resources. On the other hand, choosing BS2 because it would minimize the absolute amount of occupied resources is not a wise choice as well. As shown below, this would put BS2 almost in saturation. The solution lies in between these two approaches (tradeoff).

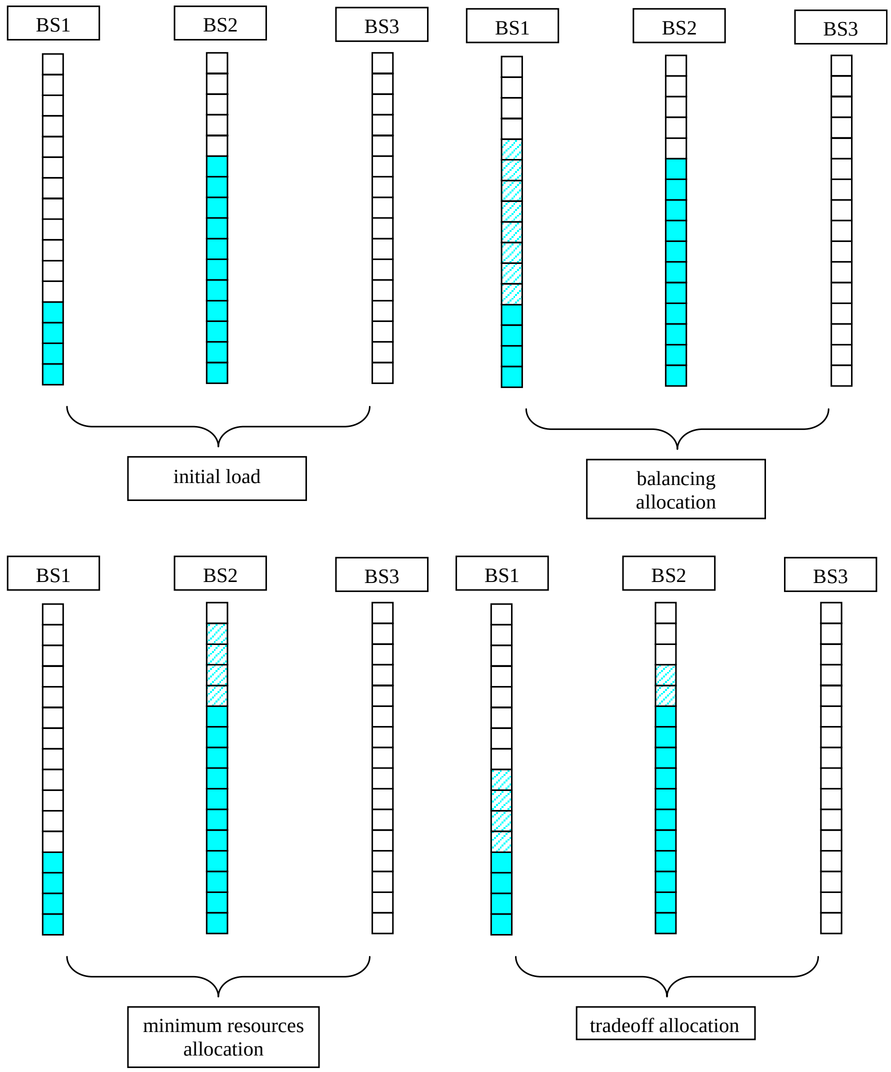

Figure IV-10: scenario analysis

This leads to the following observations / rules:

- An obvious "pure" gain is achieved when two or more servers with the same MCS are available. In this case, balancing the load is a pure enhancement.

- When two or more servers are available with different MCSs, allocation has to be carefully performed using the two highest MCSs at most. It would be ridiculous to consider the third one. Therefore here the sharing strategy involves the 3 BSs but the splitting of data will be performed through the two best BSs only.

- In this case, regardless of the allocation decision, if the amount of slots needed is already high due to medium / poor radio conditions, the final amount of resources needed shall not exceed roughly 1.5 times the minimum amount (the amount which would be granted using the best MCS only). That is, if an MCS-5 is available, highlighted rows on Table IV-3 are forbidden.

It is clear that it is difficult to design principles which would apply in all situations. Therefore the allocation schemes are somehow quite specific. For a 3 BSs sharing fixed rate E-CSD, the following allocation algorithms are considered.

- <u>Best-effort sharing</u> (overflow accommodation)

This is the simplest way to take advantage of the multiple base-stations load-sharing. The mobile uses its best BS to get most of its slots. If there is not enough space, it can get slots from the second or the third best. This algorithm is non optimum but simple to implement. Even this simple algorithm can enhance the performance of the system. It is not optimum since it is better not to wait for saturation to distribute the capacity. However it is optimum as far as the amount of resources it occupies. There is hardly any artificial load increase due to the scheme.

- <u>Limited balancing allocation</u>

For this algorithm, each new user can potentially make use of several BSs in order to balance the load, not only when congestion occurs. If there are two or more equal MCS BSs available, the method is strictly applied. For example if two BSs with MCS-5 are available, the possible allocations options for 90 Kbps are 4/0, 3/1, 2/2, 1/3 and 0/4. The option chosen will be the one minimizing the level difference between the two resources tables. For the example of Figure IV-9, it would then allocate 4 slots from the first BS.

This would lead to an equal level on both BS1 and BS2 resources. If there are two or more BSs available with different MCS, the method is applied in a limited fashion, following the rule established previously. The algorithm will still choose the option achieving the best balancing, provided that the option chosen does not require an absolute number of slots which is too high compared to the minimum required. This limitation is quite subjective. If we are dealing with high MCS, e.g two BSs are available with MCS-7 and MCS-5, it requires from 2 to 4 slots depending on the allocation option. It can still be acceptable to allocate 4 slots to the MCS-5 server if this achieves good balancing. A more conservative approach would consider only 2 and 3 slots. However, if we are dealing with lower MCS, e.g MCS-5 and MCS-2, it cannot be acceptable to allocate 8 slots from the MCS-2 server to achieve good balancing. That is why we call this method "limited" balancing. This method constantly tries to make use of the several available BSs to equal the loads of the different servers. There is no priority scheme depending on whether the user actually "belongs" to the server it requests slots from.

- <u>Limited balancing algorithm with guard channels</u>

This is a variant of the previous algorithm. The BS own resources can be shared to the neighbors up to a certain limit. If the resource occupation has reached this limit, the remaining resources are reserved exclusively for the BS traffic and cannot be used by neighbors. This can enhance the service for users who are in a situation whereby they cannot receive from more than one BS. However, averaging over all the users, this strategy may not be better than the previous one, since the shared users situation is not as good as with the previous algorithm.

The previous algorithms are implemented in the simulator. Simulation parameters are given in Table IV-4. The motivation here is to analyze the performance of the proposed scheme for middle class E-CSD fixed rate users. Both 44 kbps are 90 kbps are simulated. For the sake of simplicity, no sub-service or queuing are provided. Data users are either granted access either blocked. We assume here that some additive capacity has been deployed for a significant class of data users.

Voice / data sharing	Double boundary with voice non-preemptive priority
Voice offered load / BS	24 Erlangs
Voice blocking probability	0.08
Total number of slots / BS	35
Middle window size	5
Data only slots	8
Voice only slots	22
Data users service time	4 min
Data users arrival rates (/hour)	40, 80, 120, 160, 200
Simulation "real" duration /point	6.6 hours

Table IV-4: fixed-rate E-CSD 3 BSs sharing simulation parameters

The results from the simulations are given in Figure IV-11 and Figure IV-12. First it can be seen that the best effort sharing solution improves the performances only slightly. The limited balancing algorithm gives the best results and enhances very significantly the performances. The guard channels variant does not provide better average results, but it will definitely enhance the service of users who can take advantage of the load-sharing scheme. The results confirm the fact that the proposed scheme is more interesting for higher multi-slot class users. It can indeed be seen that the improvement for 90 kbps is greater than the improvement for 44 kbps service.

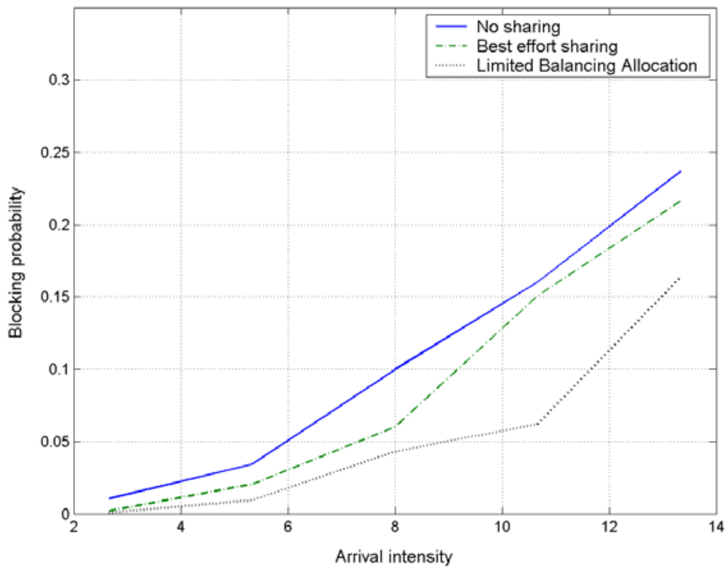

Figure IV-11: blocking probability versus arrival intensity for E-CSD 44 kbps

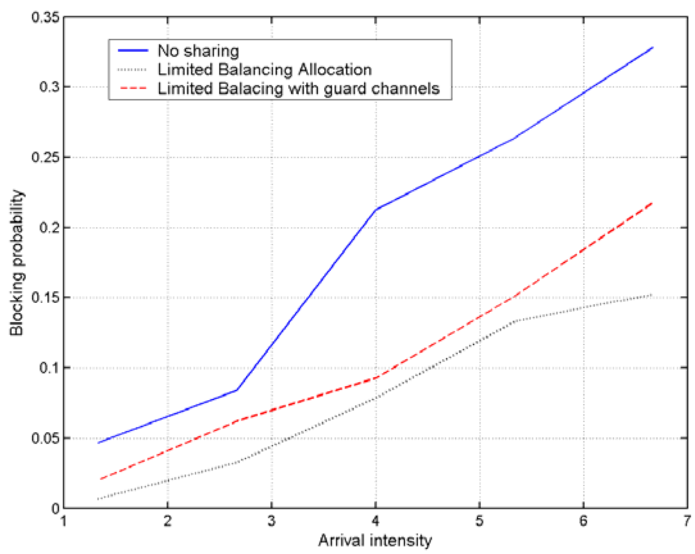

Figure IV-12: blocking probability versus arrival intensity for E-CSD 90 kbps

For 44 kbps service, the blocking probability is typically decreased by 0.02 for light load and 0.1 for high load. For 90 kbps service, the blocking probability is typically decreased by 0.05 for light load and 0.15 for high load. Another interesting fact is that high load situations lead to better performances. That is expected: this scheme is mostly interesting when resources utilization is quite high.

IV.3.2. Small super-users E-CSD class 10 service

This part aims at investigating the improvement in the number of super-users which can be accommodated with the proposed scheme over a realistic scenario.

Assumptions

The following assumptions will be taken:

- 3 BSs having each *N* channels
- One umbrella cell covering the 3 BSs sub-system is available with *N*/3 channels.
- Mixed voice users and super-users with multi-slot class 10 (between 96 kbps and 440 kbps)
- The sharing strategy involves the 3 BSs and the umbrella cell.

Since one umbrella cell is available the splitting here is potentially allowed from 3 BS: the umbrella cell and the two best BSs of the sub-system. If two BSs only are available with a sufficient SIR, the sharing algorithm makes use of these two BSs.

Algorithm

The load-sharing and splitting algorithm used follows the same philosophy as previously. It aims at balancing the different BSs load in a limited fashion. The limiting factor here is not the amount of occupied resources since the latter is fixed, but rather the offered throughput. Using a pure balancing strategy would be optimal from the traffic point of view but might give a degraded throughput which may not be desirable. This is once again due to the adaptive modulation and coding. The following rule should therefore be followed: the allocation chosen is the one which optimizes the balancing provided that the offered throughput is not less than 75% of the offered throughput obtained using the best BS only. It is implemented the following way for simplicity: the two best options for balancing are taken, and the one which gives the maximum throughput is chosen. It is clear that a more elaborate algorithm could be implemented.

Metric and complexity

The balancing metric using two BSs is rather straight-forward. Using the difference of the normalized levels is enough. The option chosen will be the one minimizing this normalized levels difference. When dealing with 3 BSs it is slightly more complicated. First a possible option for distribution is chosen (e.g 3 slots on BS 1, 3 slots on BS 2, and 4 slots on BS 3). Then given this choice the potential new levels of resources are calculated, say *n1*, *n2* and *n3*. To give a metric for minimizing the level difference between the 3 allocation tables, we choose the sum of the squares of the differences between *n1*, *n2* and *n3* and the average level. The distribution option minimizing this metric will be chosen. If the BSs involved have a different total capacity, normalization is added. If *n* denotes the average of *n1*, *n2*, and *n3*, the metric can be written the following way:

$$m = \underset{(n_1, n_2, n_3)}{\operatorname{argmin}} \left[(n_1 - n)^2 + (n_2 - n)^2 + (n_3 - n)^2 \right] \qquad \text{(IV-4)}$$

With 10 slots to distribute among 3 or 2 BSs, it is clear that there are plenty of combinations to test for the algorithm. This highlights the fact that our balancing algorithm can be very lengthy if implemented blindly. A tree-like approach can be used to simplify the number of operations. Instead of testing all the possible distributions options, the algorithm starts to test using groups of 3 channels. This makes 7 tests. The best option chosen is then refined adding or deleting 1 channel around this solution. The best option is chosen. Finally one channel is added somewhere (to make 10 slots), in a way that minimizes the metric again. Using this tree-like approach gives here 16 tests, instead of 66.

Results

The parameters of the simulation are given in Table IV-5. Once again for simplicity, no sub-service is provided. The user is either served either blocked. The performance is given is terms of the blocking probability. The results are given for the following strategy: without sharing, pure balancing and limited balancing. For each case, the average provided throughput is given.

Voice / data sharing	Double boundary with voice non-preemptive priority
Voice offered load / BS	12 Erlangs
Voice blocking probability	0.08
Total number of slots / BS	25
Middle window size	5
Data only slots	10
Voice only slots	10
Data users service time	2 min
Data users arrival rates (/hour)	8, 16, 33, 50, 66
Simulation "real" duration /point	6.6 hours

Table IV-5: super-users E-CSD class 10 simulation parameters

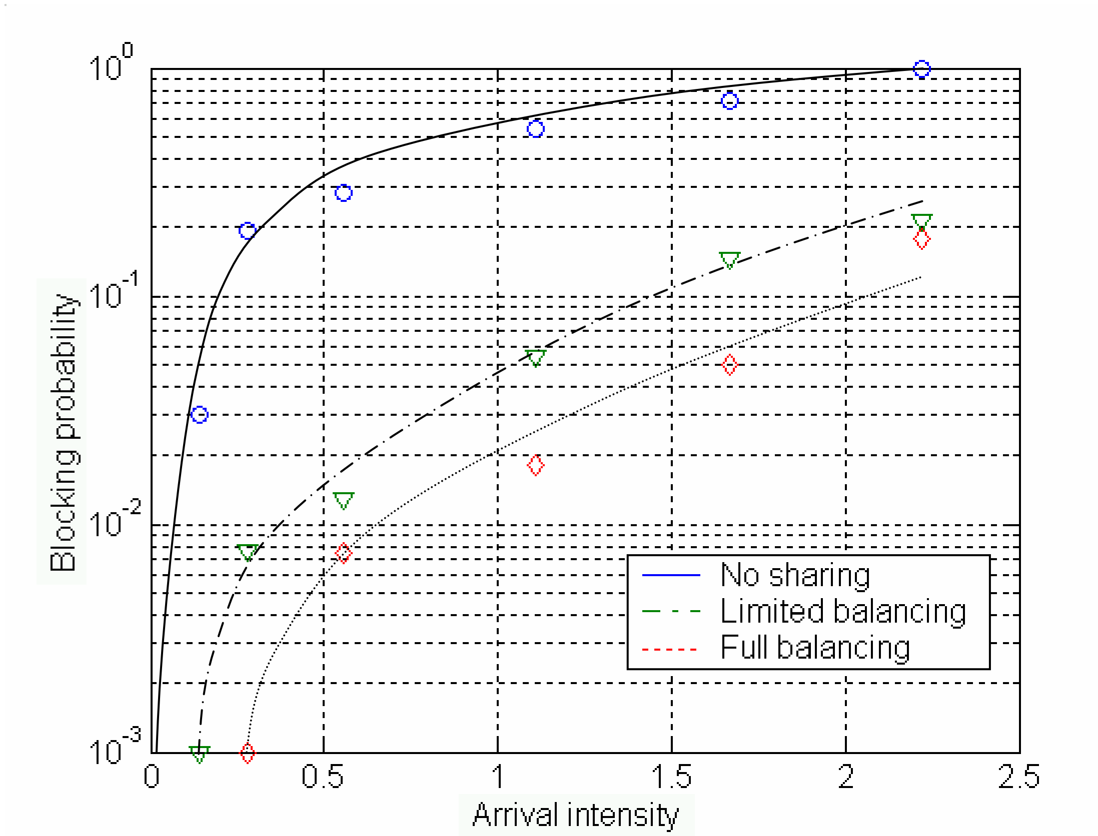

Figure IV-13: arrival intensity of super-users E-CSD class 10 versus blocking probability

From Figure IV-13 it can be seen that the balancing strategies give very good results. The results obtained here allow the derivation of the average number of accommodated users per hour, assuming that the blocking probability is between 0.01 and 0.1. Without any sharing, the overall system can accommodate from 3 to 7.5 super-users per hour, with an average throughput of 307 kbps. With limited balancing, 12 to 45 super-users per hour are accommodated with an average throughput of 261 kbps. With full balancing, 18 to 60 super-users per hour are accommodated with an average throughput of 204 kbps. The gains in capacity are indeed very significant, resulting in a slight degradation of throughput in the limited balancing case, and a more serious degradation in the full balancing case.

IV.4. Summary

This chapter focuses on resource allocation algorithm design and performance for quasi-static users. A simple analytical approach is used to derive an upper bound on the traffic gain achieved using 2 BSs load-sharing and data-splitting. The validity of this approach is tested against simulations on voice systems. It is then extended for multiple channels data users with 2 BSs. This approach is valid under symmetrical traffic and non adaptive modulation and coding assumptions (typically HSCSD). Moreover this approach is independent of the sharing strategy chosen. It is found that the gain in traffic is increasingly interesting for significant joint coverage probabilities. For the typical value of 40%, the gain for voice users ranges from 7% to 22% depending on the system size, which is significant but not extraordinary. It is found that the smaller the system (small offered load, small number of channels), the higher is the load-sharing gain. It is shown that since structurally the offered load and allocated resources for high-end data users is small, the multiple base-stations load-sharing gain can be very high for super-users. Concretely the gain can be as high as 40% for CSD class 3 users and 140% for CSD class 7 users within a mixed voice / data system of 10 and 15 channels per half-sector, respectively.

Allocations strategies are then investigated with simulations for typical E-CSD within a 3 BSs sub-system. Two case studies are taken: fixed rate 44 kbps and 90 kbps significant middle class data-services and small multi-slot class 10 super-users with umbrella cells. It is shown that a local load-balancing strategy performs the best. Load-balancing for CSD users leads in most case to data-splitting from 2 or 3 BSs . However under adaptive modulation and coding several trade-off need to be considered. In the fixed rate case, optimal balancing can lead to an artificial increase in the number of slots needed, since not only the best base-station is used. This increases artificially the resources occupation which is not desirable. In the multi-slot class 10 case, optimal balancing can lead to a degradation of the offered throughput for the user. Therefore the balancing strategy is used in a limited fashion to achieve good balancing while keeping resource occupation increase or offered throughput decrease acceptable. The blocking probability for fixed rate users 90 kbps is decreased by 0.05 for light loads and 0.15 for high loads. For 44 kbps service, the blocking probability is typically decreased by 0.02 for light load and 0.1 for high load. This confirms the fact that the improvement is better with higher multi-slot class users. The number of class 10 super-users which can be accommodated increases from 3 / 7.5 per hour to 12 / 45 per hour using the limited balancing strategy assuming one umbrella cell, a service time of 2 min, and 25 channels per half-sectors.

As a conclusion, the method of using data-splitting from several base-stations achieving load-balancing for super-users leads to a very significant increase in capacity within the same resources. It is therefore a very good candidate for integrating a small category of super-users while using the existing structure, capacity and layout. Still, concrete implementation of the proposed scheme raises numerous engineering challenges (mobility handling, architecture, signaling, handovers, RF, power consumption). It is therefore necessary to assess further the applicability of this scheme.

CHAPTER V APPLICABILITY AND CONCLUSIONS

Concrete application of the proposed scheme leads to several engineering challenges. The first section of this chapter analyses briefly these challenges. Firstly architectural implementation is not trivial. The splitting module can be located at different levels. Secondly the MAC and DLL operations involved are necessarily significant. It is probable that the decision of BSs selection will be performed at the mobile. This implies that the mobile must get information on the different BSs loads. Since several BSs are involved, special handling of the mobility is crucial to make the proposed allocation algorithms efficient. It appears that a location and direction based predictive scheme may be necessary. It would offer as well a good solution for efficient handover management. Thirdly the RF part of the mobile is more complex.

Based on these challenges, the second part presents a few interesting concrete applications. Specifically the proposed scheme can be applied for mobile hot-spots (WLAN in a car or a bus) connectivity. A mobile hot-spot is definitely a super-user for the fixed cellular infrastructure. It can be used for individual demanding super-users as well.

V.1. Engineering challenges and future research

V.1.1. Architectural considerations

As reviewed in section II.1, there are many ways to implement data-splitting. If a mobile aggregate traffic from several BSs belonging to the same operator, the logic location of the splitting module is at the Layer 2. As mentioned earlier, [13] gives interesting insight on implementation of the splitting module over wireless links with different throughput. At one end the module is at the mobile. It is less obvious where this module would be located at the other end. Following the VCN example, it would be located at the Central Base Station. It would mean that potentially every BS has this module but do not use it unless it acts as the CBS for a mobile during a certain period. Otherwise the BS acts merely as a relay to the CBS, which involves some special routing operations. (Usually the BS automatically routes the data to the Master Switching Center).

If the mobile aggregates traffic from different operators' BSs , it raises concrete problems. A significant part of the mobile operations are made using the information available from the SIM card, which is operator specific. This is namely frequencies' selection, and authentication. Some mobile terminals are multi-SIM enabled, but one SIM at a time only. It is possible to imagine that the splitting module uses the different SIM cards' information simultaneously. Similarly, from the fixed backbone point of view, it is possible to imagine a kind of Data serving node which would split the traffic going to different operators BSs through the backbone. This would create a solution transparent to higher layers, which is very desirable.

It is also possible to use a transport or network layer solution (e.g. multi-homing with one IP per operator used). However, the splitting module would have to gather lower layer information (BSs loads) in order to make efficient splitting decision. This means that the corresponding peer must have a transport or network layer supporting a multi-homed correspondent. Moreover, this would be inefficient in a high mobility environment (peer to peer decision). It remains that an efficient data-splitting transport solution is not readily available.

V.1.2. MAC / DLL considerations

As investigated in CHAPTER IV, allocation algorithms need to be implemented. It seems natural to follow a MS oriented decision scheme. That means that the mobile would require the information needed and take the decisions. Based on its needs and surrounding BSs ' loads, the mobile would make decision on which BS to use and how much resources to get from them. Similarly it could initiate itself the CBS selection and the handovers. This requires additional signaling operations. As mentioned earlier, the interesting proposal of multiple BSs handover in VCN could be used.

In a mobile environment, it is obvious that the proposed scheme increases significantly the number of HO operations. It can indeed be very inefficient if the mobile constantly changes its several serving base-stations, since it would lead to numerous re-routing and buffering operations in the BS backbone. It seems therefore necessary to include a location and direction based mechanism for BSs selection and efficient HO management. If a predictive scheme is used, the MS can decide in advance which BS to use or not. This would avoid a scenario whereby some BSs are included in the transfer then released very quickly. Some location / direction based predictive schemes [48][49] have been found to enhance handover and routing decision in mobile wireless networks. While it can be seen as a luxury for normal users, it seems very much necessary in a multiple BSs service scheme especially with high mobility.

V.1.3. RF and receiver considerations

Implementing the proposed scheme at the receiver implies more complex RF operations. Usually a mobile operates on two frequencies at a time, one for the uplink and one for the downlink. As far as GSM/EDGE systems are concerned, the operations at the mobile are made simple by time division. It means that the mobile never performs two distinct RF operations at the same time. 8 slots are available per frequency. It means for example that if the mobile uses 5 slots on the downlink and 3 slots on the uplink, it first transmits successively 3 slots on the uplink frequency then switches to the downlink frequency to receive the 5 slots. This is made possible since the BS uses a time advance mechanism while sending to the mobile. As a consequence, a normal EDGE receiver cannot transmit and receive at the same time, and the total of the uplink and downlink slots cannot exceed 8.

The proposed scheme would definitely require the mobile to receive simultaneously on different frequencies at the same time. In a first approximation it can be seen as 3 or 4 normal EDGE receivers in parallel. The mobile's RF part is therefore more complex, and as a consequence more power consuming. It is well know that GPRS/EDGE handsets suffer already from power consumption problems, since they are multi-slot enabled.

As a conclusion, implementation of the proposed scheme is challenging. As far as architectural and protocol considerations are concerned, this is after all only a software and SS7 consideration. Concerning the receiver and RF part, this would probably require a bigger handset and more battery / power resources. All of these problems would need to be seriously addressed in future research.

V.2. Typical applications

V.2.1. Individual super-users

The current offer for wireless super-users is simply inexistent. If today you want to pay and have a mobile station giving you good throughput and QoS, it simply does not exist. Coming 3G deployment will certainly improve the offer but in any case, the offered data rates are far from what users are accustomed to in everyday life. This means that there is probably always a category of demanding individual ready to pay for privileged services. The proposed scheme is an interesting solution for integration of such a class within 2.5G/3G TDMA based systems. It is interesting from the operator point of view, since it allows minimum impact on its existing capacity. As studied before, the interest holds as far as the super-user class is small, which is likely to be the case. However, the development cost of the receiver is a major concern for this category of users, since it involves hardware modifications as well. It might lead to excessive prices for the offer. We therefore think this idea might be more suited to more specific applications.

V.2.2. Mobile hot-spots

WLAN has recently attracted a lot of attention. It is seen as a cheap way of providing good wireless data-services in several locations. Typical deployment places are universities, restaurants, airports, and homes. It is not clear today whether it is really a viable business case. Forrester Research has warned [50] that it is just another bubble. It is forecasted to be actually supplanted by Bluetooth technology. In any case, the need for hot-spot services seems to be established. It is therefore very likely that very soon most of the commercially available wireless devices will be both cellular and hot-spot enabled (being Bluetooth or WLAN). It is already the case for some cellular phones and PDAs.

Following the TV Mobile philosophy of providing entertainment services of in SBS buses in Singapore, it might be of interest to provide more entertainment and services to commuters or travelers. It is said [52] that hot-spots on train might reveal to be a big revenue service. Similarly it is possible to think of hot-spots on buses or cars. This would for example allow gaming, video clips, music and chatting services (at least part of it without connectivity to the Internet). The problem arises when connectivity of the mobile hot-spot with the fixed-infrastructure is needed (service to the commuters cannot be completely offline).

This is where our proposal can be used. The mobile hot-spot would be in itself a super-user for the fixed cellular infrastructure. That is the hot-spot would emit “inside” the vehicle for on-board users and have an antenna and RF equipment “outside” for aggregated communication with a fixed cellular infrastructure. The proposed scheme can allow the mobile hot-spot to get decent connectivity for the on-board users. This is illustrated in Figure V-1. It is definitely more interesting than individual on-board users’ connectivity for the following reasons:

- The RF part can be bigger (since it is on a vehicle)
- Smart antennas even for the uplink can be used for optimization (no size constraint)
- Power consumption is no longer an issue.

- On-line services can be integrated with offline on-board services
- The vehicle direction / speed is somehow deterministic so predictive scheme can be very reliably used.
- The transceiver can be complex and use several BSs and operators resources.
- If several users in a vehicle use their handset at the same time, it can create a level of radiation which can be dangerous. Using a mobile hot-spot on board definitely solve this problem (very low power can be used).

University of San Diego [52] has started testing the concept in their shuttle bus using WLAN inside the bus and connectivity to a CDMA2000 10 miles radius base-station in the campus. This is interesting but requires its own fixed infrastructure to provide connectivity. Our proposal makes use of the existing fixed infrastructure and allows least-cost integration from the operators' point of view.

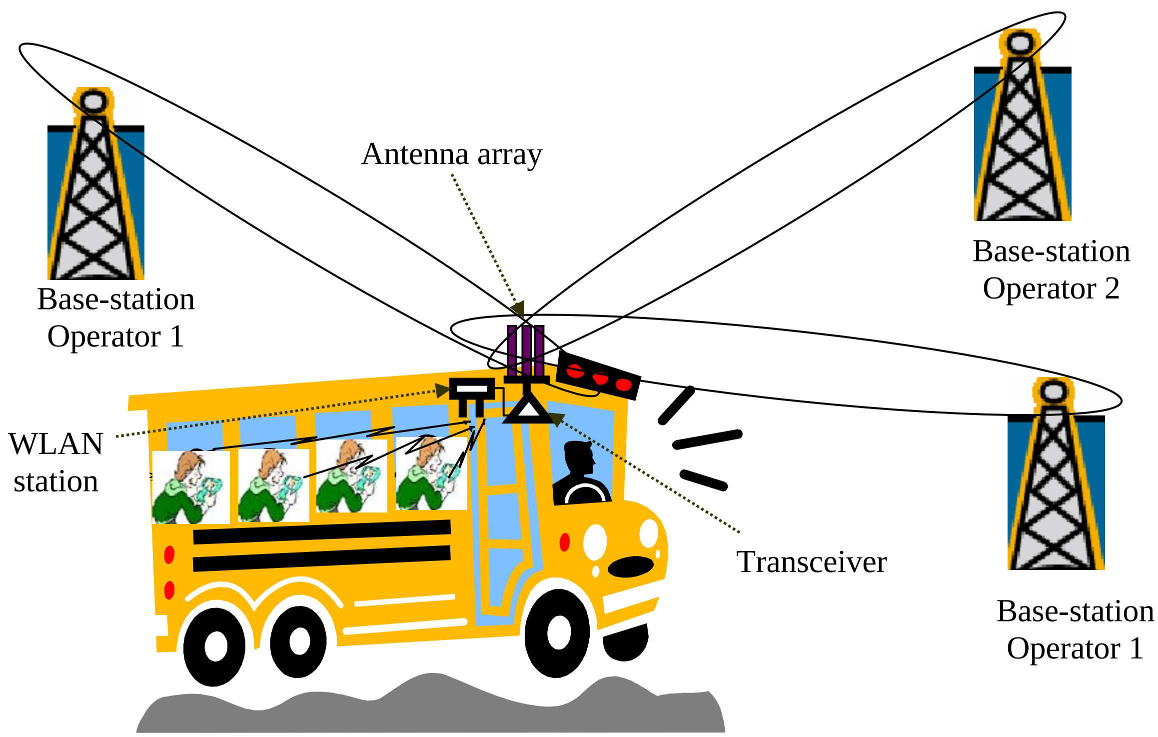

Figure V-1: mobile hot-spot infrastructure

The above mentioned idea can also be applied to cars and buses in a urban environment. However, it is not very suited for trains, which would probably require a special infrastructure.

V.3. Conclusion

This work introduces a new method for super-users integration in 2.5G cellular networks using data-splitting from several base-stations in the downlink. Integrating super-users is challenging since they require significant capacity and wireless access points usually have a limited amount of capacity to share among the users. Using several BSs helps to minimize the impact of super-users arrival in the network.

In an urban environment a MS can be almost continuously served by at least 2 BSs using cells overlapping, umbrella cells and other operators' cells. Within the same layer of cells from one operator, the probability to be in the overlapping area is typically 40% for a typical 3/9 EDGE layout. The overlapping is more significant in tight sectorized layout and will be higher than the worst case estimate most of the time. This is because the interfering cells' loads may vary.

The simultaneous usage of several BSs must be done in a way that optimizes resource occupation. It is shown that load-balancing strategies can be used and perform very well. The number of super-users accommodated with data-splitting and balancing can increase by 50% to 400% depending on the system size and the overlapping parameters compared to a normal system. This scheme is especially interesting for heavy data-users and is not much interesting for low data-rate or voice users. Implementation of load-balancing and data-splitting in an EDGE context needs to be done carefully in order to avoid an artificial increase of resource occupations or throughput degradation.

Implementation of this scheme will introduce several architecture, protocols and RF modifications. It is especially suited for aggregated super-users such as mobile hot-spots on buses and cars in an urban environment. Mobile hot-spot’s connectivity with the fixed infrastructure can be done efficiently using the proposed scheme.

APPENDIX

A. Simplification of Equation (III-20)

For any non-sectorized cellular system with frequency reuse, the direction of cells of the first tier of interferers to the serving cell are separated one to another by $\pi/3$. The angle terms in the cosine rule (III-17) can be therefore expressed:

$$\alpha_k(\theta) = \cos(\theta + \theta_o + k\pi/3)$$

where θ is the angle parameter of the mobile's location, and k ranges from *0* to *5*. Then

$$\sum_{k=0}^{5}\alpha_k(\theta) = \sum_{k=0}^{5}\cos(\theta + \theta_o + k\pi/3) = \mathrm{Re}(\sum e^{j(\theta+\theta_o+k\pi/3)})$$
$$= \mathrm{Re}(e^{j(\theta+\theta_o)}\sum_{k=0}^{5}e^{jk\pi/3}) = \mathrm{Re}(e^{j(\theta+\theta_o)}(\frac{1-e^{j2\pi}}{1-e^{j\pi/3}})) = 0$$

which gives the result:

$$\frac{1}{M}\sum_{k=0}^{5}\alpha_k(\theta) = 0$$

Similarly :

$$\sum_{k=0}^{5}\alpha_k{}^2(\theta) = \sum_{k=0}^{5}\cos^2(\theta + \theta_o + k\pi/3) = 3 + \frac{1}{2}\sum_{k=0}^{5}\cos(2\theta + 2\theta_o + 2k\pi/3)$$
$$= 3 + \frac{1}{2}\mathrm{Re}(e^{j2(\theta+\theta_o)}\sum_{k=0}^{5}e^{j2k\pi/3}) = 3 + \frac{1}{2}\mathrm{Re}(e^{j(\theta+\theta_o)}(\frac{1-e^{j4\pi}}{1-e^{j2\pi/3}})) = 3$$

Therefore:

$$\frac{1}{M}\sum_{k=0}^{5}\alpha_k{}^2(\theta) = \frac{1}{2}$$

It has to be noted that these sums can be simplified only if all the co-channel interferers are present, because k is taken from 0 to 5. Symmetrical layout is also needed so that six interferers are present.

B. <u>Moment matching derivation</u>

If Y is normal $N(\mu,\sigma^2)$, then e^Y is lognormal:

$$e^Y = \Lambda(e^{\mu+\sigma^2/2}, e^{2\mu+\sigma^2}(e^{\sigma^2}-1))$$

Let’s denote the SIR:

$$X = \Gamma^{-1} = \sum_{i=1}^{m} e^{w_i}(\frac{r}{d_i})^{\gamma} \qquad \text{(B1)}$$

where the w_i are $N(0,{\sigma_0}^2)$ (shadowing) independent and identically distributed.

We want to approximate X as a lognormal RV:

$$X = \Lambda(e^{\mu+\sigma^2/2}, e^{2\mu+\sigma^2}(e^{\sigma^2}-1)) \qquad \text{(B2)}$$

Following Wilkinson method, we match the two first moments of (B1) and (B2) to derive μ and σ. Matching the two first moments yields:

$$m_o = E(X) = e^{\mu+\sigma^2/2} = \sum_{i=1}^{m}(\frac{r}{d_i})^{\gamma} E(e^{w_i}) = \sum_{i=1}^{m}(\frac{r}{d_i})^{\gamma} e^{{\sigma_0}^2/2}$$

and

$$m_1 = E(X^2) = e^{2(\mu+\sigma^2)} = E\left(\sum_{i=1}^{m} e^{w_i}(\frac{r}{d_i})^{\gamma}.\sum_{i=1}^{m} e^{w_i}(\frac{r}{d_i})^{\gamma}\right)$$
$$= \sum_{i=1}^{m}(\frac{r}{d_i})^{2\gamma} E(e^{2w_i}) + 2\sum_{i=1}^{M_k-1}\sum_{j=1}^{M_k}(\frac{r^2}{d_i d_j})^{\gamma} E(e^{w_j})E(e^{w_i})$$

which gives the following system for μ and σ^2:

$$\begin{cases} e^{\mu+\sigma^2/2} = \sum_{i=1}^{m}(\frac{r}{d_i})^{\gamma} e^{{\sigma_0}^2/2} \\ e^{2(\mu+\sigma^2)} = \sum_{i=1}^{m}(\frac{r}{d_i})^{2\gamma} e^{2{\sigma_0}^2} + (2\sum_{i=1}^{M_k-1}\sum_{j=1}^{M_k}(\frac{r^2}{d_i d_j})^{\gamma})e^{{\sigma_0}^2} \end{cases}$$

Taking the logarithm of the two equations gives a linear system in μ and σ^2. The solution is straightforward and gives (III-29) and (III-30) after *ln* to *log10* adaptation.

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