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Inter-Cell Interference Coordination Techniques in Mobile Networks

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Master's Thesis

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BUDAPESTI MÛSZAKI ÉS
GAZDASÁGTUDOMÁNYI EGYETEM
TÁVKÖZLÉSI ÉS
MÉDIAINFORMATIKAI TANSZÉK

DIPLOMATERV

Reider Norbert

mérnökjelölt részére

Feladat: Cellák közötti erőforrás megosztó algoritmus tervezése és szimulációs vizsgálata mobil hálózatokban

Tervezzen egy algoritmust mobil hálózatok szomszédos cellái közötti erőforrás megosztásra, OFDM rádiós technológiát feltételezve. Az algoritmus képes legyen a rádiós erőforrások oly módon történő elosztására, hogy a szomszédos cellák által egymásnak okozott interferencia lehetőleg minél kisebb legyen.

- Az algoritmusnak integrálhatónak kell lennie a rádiós ütemező algoritmusával, és figyelembe kell vennie a bázisállomások közötti kommunikáció minimalizálásának szempontját.
- Valósítsa meg az algoritmust az adott szimulációs környezetben.
- Elemezze az algoritmus működésének helyességét szimulációkkal és hasonlítsa össze a hálózat rádiós teljesítményét a koordinációt nem használó esettel.

Záróvizsga tárgyak:

IP hálózatok és alkalmazások vizsgálata (*)
Valószínűségszámítás
Távközlő hálózatok

A feladat benyújtásának határideje: 2007. május 18.

Tanszéki konzulens: Dr. Vidács Attila

Ipari konzulens: Dr. Rácz András (Ericsson Kft.)

A tervezés bírálója:

Budapest, 2007. február 21.

(Dr. Sallai Gyula)
egy.tanár, tanszékvezetõ

Ez a feladatlap a diplomatervhez csatolandó.

Az ipari konzulens véleménye:

A tanszéki konzulens véleménye:

Nyilatkozat

Alulírott Reider Norbert, a Budapesti Műszaki és Gazdaságtudományi Egyetem hallgatója kijelentem, hogy ezt a diplomatervet meg nem engedett segítség nélkül, saját magam készítettem, és a diplomatervben csak a megadott forrásokat használtam fel. Minden olyan részt, melyet szó szerint, vagy azonos értelemben, de átfogalmazva más forrásból átvettem, a forrás megadásával egyértelműen megjelöltem.

Budapest, 2007. május 18.

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Reider Norbert

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Abstract

The rapid growth of the population of mobile users demands the fast development of mobile wireless communication and technology. The new trends in wireless telecommunications desire higher user bit rates and lower delay requirements, among others from the user point of view. The wireless mobile system has to meet these requirements. Nowadays the radio interface seems to be the bottleneck of such a wireless system, because the radio resource is limited and quite expensive, hence the efficient use of the radio spectrum is very important from the cost of service point of view. A reduction in the cost and higher bit rates can be achieved, for example, by more efficient reuse of frequency. Therefore, the efficient use of radio spectrum plays a very important role in maximizing the utilization of the system as well.

In cellular networks the radio spectrum is divided into a set of disjoint radio channels that are assigned to mobile users. The technique that decides which channel is used by a mobile user is called channel allocation. Any of the channels can be used simultaneously in any cells if the interference generated by mobiles using the same channel is acceptable. A suitable channel assignment algorithm can reduce interference by coordinating the allocation of channels to users in adjacent cells, which results in higher user bit rates due to lower level of interference. Therefore, the efficiency of a channel allocation technique has a high impact on the capacity of the system as well.

In my thesis, first I start by giving an overview of the most important radio channel allocation algorithms that can be used for assigning radio channels to users more efficiently in order to provide better services for mobile terminals. Then I introduce the radio resource assignment scheme in the investigated next generation mobile networks.

To improve the existing channel assignment scheme in this mobile system, a set of algorithms is proposed which takes the interference between adjacent cells into account and attempts to coordinate the radio resource assignment in order to minimize the interference. Five different variants of this algorithm are presented in detail. To evaluate the developed algorithm and its variants I extended a radio network simulator developed by Ericsson. Finally the simulation results and their evaluation are discussed.

Kivonat

A mobil felhasználók számának rohamos növekedése igényli a mobil vezetéknélküli kommunikációs technológia egyre gyorsabb fejlődését. Ezenkívül nem csak a mobil felhasználók populációja növekszik, hanem egyúttal a mobil hálózattal szemben támasztott igények is emelkednek. A mobil rendszernek többek között egyre nagyobb adatsebesség, illetve egyre kisebb késleltetés követelményeket kell kielégítenie. Manapság egy ilyen mobil hálózatban a rádiós interfész mutatkozik szűk keresztmetszetnek, mivel a rádiós erőforrás korlátos és meglehetősen drága, ezért a rádiós interfész hatékony kihasználása nagyon fontos a rendszer kapacitása, és ezáltal a szolgáltatás költsége szempontjából is.

A cellás mobil hálózatokban a rádiós erőforrás diszjunkt rádiós csatornákra osztják fel, amelyeket igény szerint a mobil felhasználókhoz rendelnek. Csatorna hozzárendelésnek nevezik azt a technikát, ami meghatározza, hogy az egyes rádiós csatornákat mely mobil felhasználók használhatják. A csatorna hozzárendelési technika bármely rádiós csatornát kioszthatja a felhasználóknak bármely cellában, ha az interferencia, melyet azon mobil terminálok okozzák, melyek ugyanazt a csatornát használják, egy elfogadható értéken belül van. Egy megfelelő csatorna hozzárendelés képes az interferenciát csökkenteni, és ezáltal az elért bitsebességet növelni, oly módon, hogy koordinálja a csatorna hozzárendelést az egyes cellákban figyelembe véve a szomszédos cellákban a mobil terminálokhoz rendelt csatornákat. Emiatt a csatorna hozzárendelés hatékonysága nagy hatással van a rendszer kapacitására is.

A diplomatervben először bemutatom a legfontosabb csatorna hozzárendelési technikákat, amelyek megpróbálják minél hatékonyabban mobil terminálokhoz rendelni rádiós csatornákat a jobb kihasználtság és a magasabb bitsebesség elérése érdekében. Majd részletesen bemutatom a vizsgált újgenerációs mobil hálózatban alkalmazott csatorna hozzárendelési technikát.

Az ebben a mobil hálózatban alkalmazott csatorna hozzárendelés továbbfejlesztése érdekében öt algoritmust javasoltam, mely a szomszédos cellák közötti interferenciát próbálja csökkenti a rádiós erőforrás felhasználóhoz rendelésének koordinálásával. A javasolt algoritmusok vizsgálata érdekében kibővítettem egy rádiós szimulátort, melyet az Ericsson fejlesztett. A diploma végén a kapott szimulációs eredményeket mutatom be, és részletesen kiértékelem azokat.

Table of contents

List of Figures

1. Introduction

The population of mobile users is growing rapidly. There are also more and more applications that require high bit rates and low delay parameters to provide different kind of multimedia services in order to present information more effectively. The new generation mobile system has to meet these requirements to satisfy the demands of mobile users. The frequency spectrum is a very expensive and limited resource, hence the optimal use of the radio resources is one of the most important research topics. Today the packet switched service is getting more and more important and becoming the dominant traffic in the wireless systems. Therefore, new techniques are needed for the efficient use of the limited radio resources that are optimized for packet switched data.

1.1 Radio link as a limited resource

In cellular networks the radio spectrum is divided into disjoint parts, called radio channels. Any of the channels can be used simultaneously in a cell if the interference caused by mobile terminals using the same channel in other cells is acceptable. The channel allocation (or channel assignment) technique is responsible for assigning channels to mobile users. Therefore, the objective of most of the channel allocation schemes is to achieve such an assignment where the level of generated interference is the lowest, which, in turn, will result in higher user bit rates. The channel assignment schemes are used for circuit and packet switched services as well. The main principle behind different schemes are the same, reduce interference to achieve improvement in system capacity.

The investigated mobile network is also a packet switched cellular system using Orthogonal Frequency Division Multiplexing (*OFDM*) radio air interface. Such a cellular mobile system is the Long Term Evolution (*LTE*) system, which is referred to as the investigated mobile network in the thesis. The radio spectrum is divided into resource blocks in frequency and in time domain as well. The frequency domain is represented by the *OFDM* carriers. Here, the channel allocation technique assigns these radio blocks to users taking the interference into account. The potential channel assignment schemes are similar to the ones in circuit switched systems, where the resource block is represented by a single circuit channel.

The level of generated interference is caused by such mobiles that use the same resource block in other cells. In order to reduce the interference a channel assignment technique is needed which takes the channel assignment of other cells into account in order to try to avoid the cases when two mobiles use the same resource block. Such channel allocation technique is referred to as Inter-Cell Interference Coordination (*ICIC*). The generated interference is particularly significant when two mobile terminals use the same resource block in cells that are adjacent with each other. In my thesis a set of *ICIC* channel assignment techniques is proposed which takes the interference between neighbor cells into account.

1.2 Structure of the thesis

The structure of my thesis is the following. In section 2, I start by giving an overview of the most important radio resource assignment schemes used in circuit switched networks. Then in section 3, the radio resource assignment scheme is introduced in the investigated next generation mobile network giving a base to my work. The topic of the next section is the description of the developed algorithm which tries to use the radio resources more efficiently in such a way so that it takes the inter-cell interference into account in order to achieve improvement in user bit rate as well as in system capacity (section 4). Then the simulation environment and the results of the simulation are presented regarding to the proposed algorithm (section 5, 6). The summary of my work can be found in the last part of the thesis (section 7).

2. Related work

Many channel allocation techniques were published in the last two decades. In this section I present the most important ones that can be associated to my work in which a packet switched mobile network is investigated in terms of the used channel allocation scheme.

All of the channel allocation techniques, described below assume that a mobile terminal initiates and terminates voice calls and a separate radio channel will be allocated for each call. After a call has been terminated the channel used by the mobile terminal becomes free. This means that the mobile system provides circuit switched services for mobile terminals. The following channel allocation schemes are based on these assumptions.

Although, the described schemes are used in circuit switched systems the principles could be reused in packet switched systems as it can be seen in the next section.

2.1 Channel Assignment schemes

Before describing the different channel allocation schemes, some basic definitions are introduced. As it was mentioned in previous section, the radio spectrum is divided into a set of disjoint radio channels. Any of the channels can be used at the same time if the interference generated by the other cells is acceptable. (This interference can be reduced by suitable channel separation.) Several techniques can be used to divide radio spectrum into channels, such as time division, frequency division, or code division. In case of time division, the time is divided into disjoint intervals, called time slots and a time slot represents a radio channel. Different mobile terminals can use different time slots. In frequency division, the frequency is divided into disjoint frequency bands and the channel separation is determined by these bands. In case of code division, different modulation codes determine the radio channels used by mobile terminals. The reason why it is worth to separate radio spectrum into channels, among others, is that the received signal-to-interference ratio is higher and therefore the efficiency of the system is higher as well and more calls of users can be served [6].

Let's consider that the mobile terminal (also referred to as User Equipment, *UE*) *i* communicates using the channel *k*. Due to the physical characteristics of radio environment, channel *k* can be reused at the same time by another mobile terminal *j* if the two terminals are spaced at a sufficient distance from each other. All terminals which use the same channel are called *co-channel sets* or simply *co-channels*. The minimum distance at which co-channels can be reused is referred to as *co-channel reuse distance*. The minimum distance assumes that the level of signal-to-interference ratio (S*IR*) in each co-channels are above a certain threshold *(*SIR_{min}). The signal represents the received signal power in a channel and the interference represents the sum of received signal power of all co-channels. Due to the propagation path-loss in the radio environment, the received power decreases as the distance between the receiver and the transmitter increases.

At distance *d*, the average received power is $P_T d^{-\alpha}$, where P_T is the average transmitter power and α, called *attenuation factor*, is the number in the range of 3-5 depending on physical environment. (Important to note that this model does not take into account other radio propagation effects such as the shadowing or multipath fading. Mean value of these effects are zero, therefore, the average received power depends only on the distance *d* and the transmitter power P_T.) Thus, the average *SIR* at the receiver mobile station is given by:

$$SIR = \frac{P_t d_t^{-\alpha}}{\sum_{i=1}^{N} P_i d_i^{-\alpha} + N_0} \qquad (1)$$

where P_t represents the average transmitter power of transmitter station *T* with which the receiver mobile terminal *R* communicates, this receiver *R* is at the distance d_t from transmitter *T*. Furthermore, *N* is the number of the other transmitting base stations S_i which use the same channel as *R* to communicate to other mobile terminals, P_i is the average transmitter power of S_i stations, d_i is the distance between *R* and S_i base stations ($i \in 1,2,...,N$) and N_0 is the constant environmental noise value. Figure 1 shows an example for the interference in downlink, where N is 5.

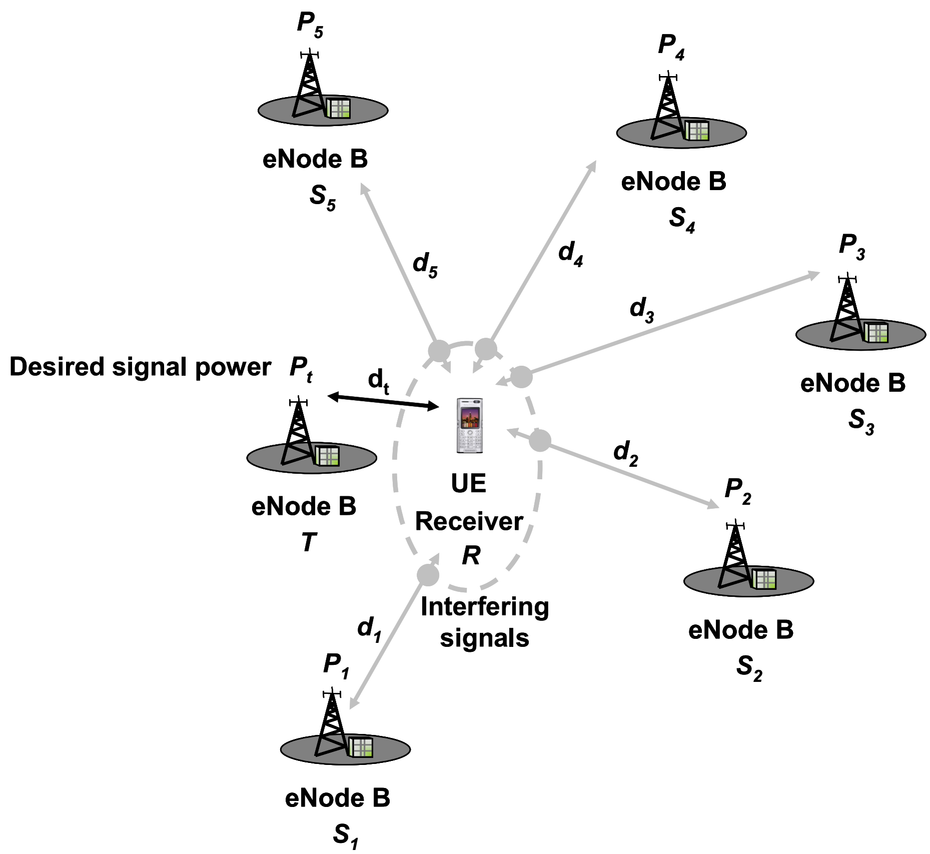


Figure 1: Interference in downlink

In order to increase the level of *SIR* at the receiver station *R*, different techniques can be used, for example the distance between *R* and S_i stations can be increased by a frequency reuse. Another technique to increase *SIR* at the receiver R can be to reduce the transmitter power of S_i and increase the transmitter power of transmitter *T*.

After this short introduction, an overview of the most important channel allocation schemes that are connected to my work is presented. They can be divided into three major parts, Fixed, Dynamic and Hybrid Channel Allocation based on how co-channels are separated. The most of the following channel assignment methods try to increase the level of the signal-to-interference ratio by separating co-channels.

2.1.1 Fixed Channel Allocation

With Fixed Channel Allocation schemes [6], the area of the wireless system is divided into cells and a number of channels are assigned to these cells depending on the desired level of signal-to-interference ratio. Therefore, there is a definite relationship between each channel and each cell. The number of channels assigned to one cell is the same in each cell, that is, the channel distribution among cells is uniform. As mentioned above, the total number of channels is divided into sets and the minimum number of these sets *N* which can serve the coverage area at *σ* co-channel reuse distance is given by the following formula [1].

$$N = \frac{\sigma^2}{3} \qquad (2)$$

Here *σ* is defined as *D/R*, where *D* is the distance between co-channel sites and *R* is the radius of the hexagonal cell. *N* can be only such integer values that satisfy the formula, $i^2 + j^2 - ij$, where *i* and *j* are integer numbers. *N* is referred to as *reuse factor* or *reuse ratio*. Figure 2 shows an example for *N=3* (*σ=3*) and *N=7* (*σ=4.58*) cases.

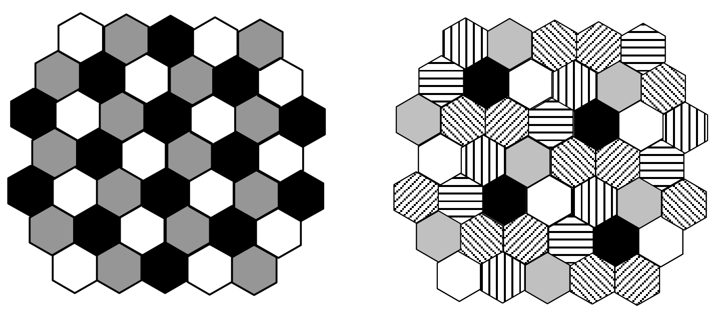


Figure 2: Channel allocation sets for *N=3* and *N=7*

The Fixed Channel Allocation schemes are not able to handle variable traffic conditions due to uniform distribution of channels in cells but they are very simple. The traffic load can be non-uniform in a cellular system and the uniform channel allocation can reduce capacity and utilization of the system significantly [6]. There are several Fixed Allocation schemes which adjust the number of channels in a given cell depending on the load in it, such as the Non-uniform Compact Pattern Channel Allocation [5]. This scheme attempts to minimize the average blocking probability in the whole system.

Another Fixed Channel Allocation scheme is called Channel Borrowing [2]. It uses the idea that unused channels from lightly loaded cells can be borrowed by the heavily loaded ones if the distance of cells is greater than the co-channel reuse distance σ. This means that the channel can be borrowed by a cell if the usage of the channel in the cell does not interfere with other channels. The re-assignment of a channel can be done periodically according to the traffic load variations based on previous measurements. When a channel is borrowed by a cell, other cells are not allowed to borrow it. This phenomenon is called channel locking. For example in case of $\sigma = 3$ (with reuse distance of one cell) the borrowed channel is locked in three adjacent cells as it can be seen in Figure 3.

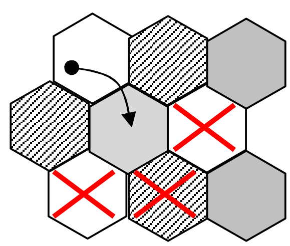


Figure 3: Channel locking with $\sigma = 3$

Several other Channel Borrowing schemes were proposed. They differ in the way an unused channel is selected [2].

2.1.2 Dynamic Channel Allocation

As it was mentioned before, due to the short term variation of traffic load in cellular systems, Fixed Channel Assignment schemes are not able to achieve high efficiency. Dynamic Channel Allocation schemes attempt to eliminate the drawback of Fixed Channel Allocation by keeping all of the radio channels in a central pool. The channels are assigned to a mobile terminal as needed if the given SIR_{min} threshold is satisfied. After a call is completed, the used radio channel is returned to the pool.

The drawback of this technique is that it requires a central coordinating entity that maintains the central pool of channels.

In general, more than one channel is able to satisfy the required interference conditions. Therefore, a strategy is required to select a channel to be assigned to a call. The Dynamic Channel Allocation schemes attempt to evaluate the cost of using a channel and they select the one with minimum cost. The different Dynamic Channel Allocation schemes differ in the selected cost function [4].

Compared to Fixed Channel Allocation, the described solution is more complex, but more flexible as well from the adaptation of traffic load point of view.

2.1.3 Hybrid Channel Allocation

Hybrid Channel Allocation combines the advantages of the Dynamic and the Fixed Allocation schemes. It is used, because the Dynamic Channel Allocation becomes less efficient than the fixed one at high traffic load [6]. With Hybrid Allocation, the total number of radio channels is divided into two sets, fixed and dynamic. The fixed set contains channels that can be used only in the assigned cells as in case of the Fixed Allocation. The other set of channels can be used by all users in order to increase flexibility of the system as in case of Dynamic Channel Allocation. When a mobile terminal wants to use a channel in a cell and all of the channels that are assigned its cell are busy, then a free channel from the dynamic set will be assigned to the terminal.

2.2 Reuse Partitioning

The Reuse Partitioning is another technique to achieve higher bit rates in cellular systems [1]. With Reuse Partitioning, each cell is divided into two or more concentric partitions. The mobile terminals that are closer to the base station receive higher *SIR* as the interference caused by mobile terminals in adjacent cells using the same radio channel is lower. Therefore, they can reduce the transmission power level to reach the desired *SIR* value. This also means that the distance between cells using the same channel (co-channel reuse distance) can be smaller in the inner partitions of the cell than in the outer ones, which results in higher system capacity due to the tighter reuse. Figure 4 shows an example to reuse partitioning.

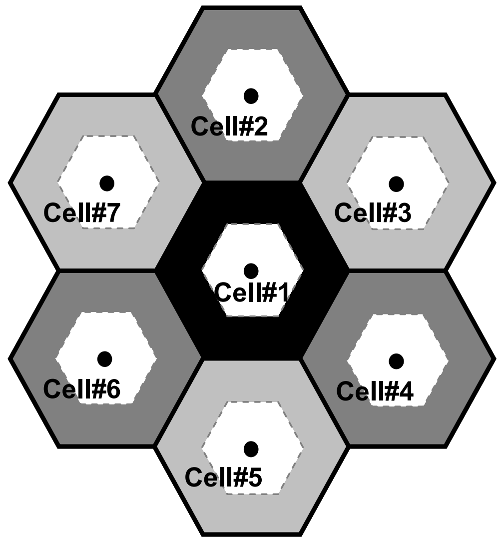


Figure 4: 7-cell system layout with 2-region reuse partitioning

The main idea of Reuse Partitioning is to reduce signal-to-interference ratio if the given cell has already reached the desired transmission quality. In other words, it attempts to produce an *SIR* distribution in the whole system which satisfies the system quality requirements and also brings some gain in system capacity. There are numerous Reuse Partitioning methods that can be divided into two major parts, Fixed and Adaptive Reuse Partitioning schemes [6], but the Reuse Partitioning techniques can be combined with different Channel Allocation schemes as well [3]. In the following I present an overview of two Fixed Reuse Partitioning methods, Simple Reuse Partitioning and Simple Sorting Channel Assignment Algorithm.

In case of Simple Reuse Partitioning the radio channels are divided into fixed disjoint groups. The channel assignment within a group is determined by the reuse factor. The reuse factor was also defined in 2.1.1 by the following ratio.

$$N = \frac{\left(\frac{D}{R}\right)^2}{3} \tag{3}$$

where D is the distance between co-channel sites and R is the radius of the hexagonal cell. Figure 5 shows an example using $N_A = 3$ and $N_B = 7$.

The mobile terminals with the best *SIR* value are assigned to the group of channels having the smallest reuse factor. The mobile terminals with the lowest *SIR* value are assigned to the group of channels having the largest reuse factor. This functioning results that the channel having a small reuse factor will be assigned to the mobile terminals that are closer to the base station.

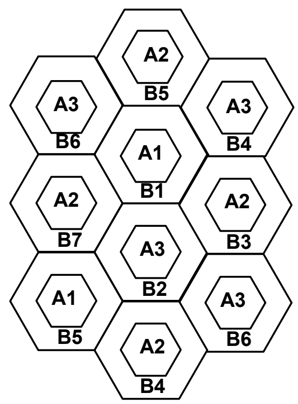


Figure 5: Hexagonal cells are partitioned into two reuse groups with $N_A = 3$ and $N_B = 7$

Simple Sorting Channel Assignment Algorithm is a generalized reuse partitioning method. Each cell is divided into a number of concentric partitions and it is assigned to a number of channels the same way as in case of Simple Reuse Partitioning. The base station measures the received *SIR* value for each mobile terminal and sorts the measurements into descending order. Let's denote M the number of available channels in the entire cell. Then the set of at most M mobile terminals with the largest *SIR* value are assigned to the available channels M. The mobile terminal in the set with the smallest *SIR* value will be assigned to a channel from the outer cell partition. The assignment of channels to mobiles continues until all channels from the outer partition are used according to ascending *SIR* values of mobiles. Then the base station continues assigning channels until all mobile terminals in the set have been assigned to channels. The functioning of the Simple Sorting Channel Assignment Algorithm is presented in Figure 6.

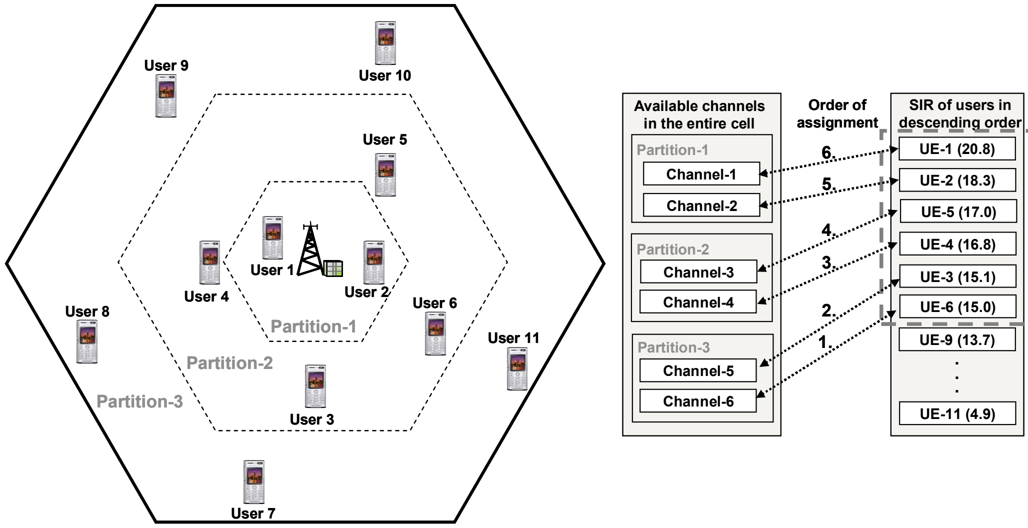


Figure 6: Example to Simple Sorting Channel Assignment Algorithm

The idea behind this algorithm in terms of sorting users according to the measured value of *SIR* is also used in one of the variants of the proposed algorithm, but the path gain value is taken into account instead of *SIR* when the users are sorted. The algorithm is described in subsection 4.2.4.

Another important issue is how to assign actual channels to mobile terminals, because the sorting scheme only determines that from which partition a channel should be used by the mobile terminal. If all cells started assigning channels by using the first channel in the group, then it would result high interference between groups of the channels. The random selection would be a simple solution to this problem [7].

The drawback of the fixed reuse partitioning is similar to the drawback of the Fixed Channel Allocation, is that they are not able to handle traffic which varies in time. Adaptive Reuse Partitioning tries to avoid the above mentioned problem in such a way so that any channel in the system can be used by any base station if the signal-to-interference ratio is above the limit. Several different Adaptive Reuse Partitioning schemes have been published based on this idea. These schemes do not connect directly to the present study. Therefore, the descriptions of these ones are not included in the thesis.

2.3 Frequency Planning

In the previous subsections the channel assignment techniques were presented. All of them try to find the best way of assigning radio channels to calls to achieve higher efficiency of the system.

Then, it can be an important question, what is the minimum number of channels that are needed to handle a given traffic with a predefined blocking probability. One solution uses a graph coloring algorithm [8]. This method creates a graph in such a way so that the vertices represent the mobile terminals in the system and an edge interconnects two vertices if and only if two mobiles cannot use the same channel, due to unacceptable level of interference. This means that two vertices are interconnected by an edge if and only if the certain SIR_{min} threshold is not satisfied. Then a graph coloring algorithm can be used to find the minimum number of colors that is the minimum number of required channels as well. Coloring algorithms do not color two vertices in the same color if and only if they are interconnected by an edge. As known, the coloring problem is *NP-complete*, therefore only heuristics can be used.

2.4 Power Control

Some channel assignment algorithms can also use power control to achieve a certain level of *SIR*. As it was introduced in section 2.1, the *SIR* value is proportional to the power level of the desired signal and inversely proportional to the power level generated by the co-channels. Thus, the *SIR* level can be increased by increasing the power level of the desired signal or decreasing the power level of the interfering signals. Important to note, that increasing the power level of the desired signal increases the interference at other stations using the same channel. Therefore, the power control schemes try to increase the *SIR* in the system by measuring the received power and adjusting (decreasing or increasing) the transmitting power in order to maximize the minimum level of *SIR* in the entire system which results in lower reuse distance. Therefore, this technique can achieve significant increase in the system capacity [6].

3. Radio resource assignment in Long Term Evolution system

In the previous section the high-level description of several channel allocation schemes were presented. These schemes try to increase the efficiency of the radio resources by separating the co-channels. The topic of this section is the description of the channel assignment scheme used in the investigated mobile network.

3.1 Introduction of Long Term Evolution system

In this subsection I briefly introduce the investigated mobile network and I point out the occurring correspondence to the channel assignment schemes described in section 2.

The 3rd Generation Partnership Project (*3GPP*) is working on the standardization of new generation of the third generation (*3G*) mobile networks planned to be ready at the end of this year. In order to increase capacity and reduce latency, among others, a new radio interface was proposed for the Radio Access Network (*RAN*) part of the system, referred to as Long Term Evolution (*LTE*) based on *OFDM* technology. In addition, the architecture of the *RAN* is also changed. The radio related functionality such as control functions (admission control, handover control, etc.) and user plane functions (Radio Link Control (*RLC*) and Medium Access Control (*MAC*) protocols) are terminated in the base station [10]. Therefore, there is no central coordination entity in the system which makes the realization of all kinds of inter-cell radio resource coordination, such as the *ICIC* more challenging.

In *LTE* 1-reuse of frequency is used, which means that the whole frequency band is available simultaneously in any cell. The entire radio resource can be used in each cell without any constraint. As in *LTE* there is no central Radio Resource Management (*RRM*) coordination entity which is responsible for frequency planning and controlling co-channel interference, among others. Therefore, if coordination of assignment is needed then autonomous algorithms can be used in base stations or communication is required between them. The higher level of interference due to tight reuse of frequency is decreased by for example, power control applied in uplink.

My investigations have been made in the *LTE* system that is referred to as the investigated mobile network in the thesis. In this paragraph the brief introduction of the *OFDM* technology used in *LTE* can be found. The *OFDM* is a multi-carrier modulation scheme [9]. The spectrum is divided into closely-spaced orthogonal sub-carriers. Each sub-carrier is modulated with a conventional modulation scheme such as Quadrature Phase-Shift Keying (*QPSK*) or Quadrature Amplitude Modulation (*QAM*). One of the main advantages of *OFDM* is the orthogonality of sub-carriers. This means that there is no crosstalk between sub-carriers and no need for inter-carrier guard bands, therefore this is a robust solution against narrow-band co-channel interference. Important to note, that a very accurate frequency and time synchronization is required between transmitter and receiver in order to ensure orthogonality of the *OFDM* sub-carriers. A little deviation in the frequency or time synchronization causes crosstalk between sub-carriers, i.e. inter-carrier interference. In practice, the *OFDM* signals are generated using the Fast Fourier Transform (*FFT*) algorithm.

3.2 Scheduling concept as a resource assignment scheme

In Long Term Evolution the radio spectrum is divided into radio blocks in frequency and time domain, where the frequency is represented by the *OFDM* carriers as it can be seen in Figure 7. The radio block is also referred to as “chunk” or Physical Resource Block (*PRB*).

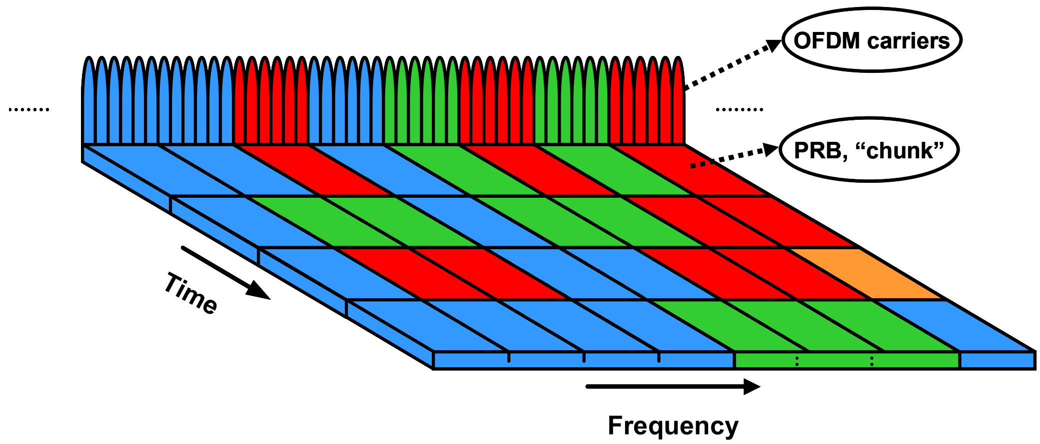


Figure 7: Time-frequency radio blocks ("chunks")

As far as the radio resource assignment is concerned in the *LTE* system, the schedulers in base stations play the most important role. The scheduler entity is responsible for assigning chunks to mobile users both in downlink and uplink to utilize the radio resource so that the output of the system is optimized. In Figure 7 different colors denote the assignment of chunks to different users. In the scheduling concept the time is divided into short intervals referred to as Transmission Time Interval (*TTI*), that is the frame period of the radio transmission (*TTI* is only 1 ms in *LTE*). The base station makes the scheduling decision in every *TTI* period of time. Too long *TTI* duration can result in unsatisfied users, because it increases the radio interface delay. Too short *TTI* can result in high processing burden on the Layer 1/Layer 2 transmitters and receivers. This means that the scheduler has to serve all of its queues regularly using an acceptable *TTI* duration. Compared to the channel allocation schemes described in section 2, it can be seen as the radio resource is assigned to the mobile terminal only for one *TTI*, not as long as a call is active.

In the following paragraphs the principle of the basic functioning of the scheduler is described. As it was mentioned before the resource block is analogue to radio channel concept in the described channel allocation schemes, this means that a resource block can represent a radio channel. For each resource block a quality level can be determined, called Channel Quality Indicator (*CQI*), which tells how high the level of signal-to-interference ratio is on that channel. This value depends on the position of the mobile terminals during the session. Important to note, that the quality on different channels can also be different to the same mobile terminal. On the other hand the *CQI* value can vary over time as the user moves. This means that the scheduler should take the *CQI value* into account in order to increase the system capacity.

From the user point of view, each user in a cell has one or more data queues where its data waits to be served. In the downlink (*DL*) these queues are located in the base stations, while for the uplink (*UL*) traffic they are located in the terminal. Due to the support of Quality-of-Service (*QoS*) in *LTE*, one mobile user can have multiple services which results in more than one queue for the user. This separation of traffic is necessary, because the requirements of different type of traffic can be different. For example, a mobile terminal downloads a video clip using Transmission Control Protocol (*TCP*) and at the same time uses a Voice over Internet Protocol (*VoIP*) application. The delay requirements of the two traffic types are different. The *TCP* packets can be delayed by more than hundred milliseconds, because it carries elastic traffic (best effort service) and *TCP* can adapts its transmission rate to the assigned radio resources. The *VoIP* traffic expects a certain bit rate in order to provide an acceptable quality of the speech. Therefore, the *VoIP* frames must be delivered in about 50 milliseconds, otherwise these frames have to be dropped. In addition, signaling messages should get the highest priority to ensure adequate functioning of the system. This means that the scheduler must take the *service priorities* into account as well.

Other important requirement is that the scheduler must ensure a certain degree of *fairness*. This means that all data queues of all users in the corresponding cell must be served regularly in order to avoid starvation. Otherwise, higher layer protocols may react with timer expiry and retransmission before they finally give up. The illustration of the basic functioning of scheduler can be seen in Figure 8.

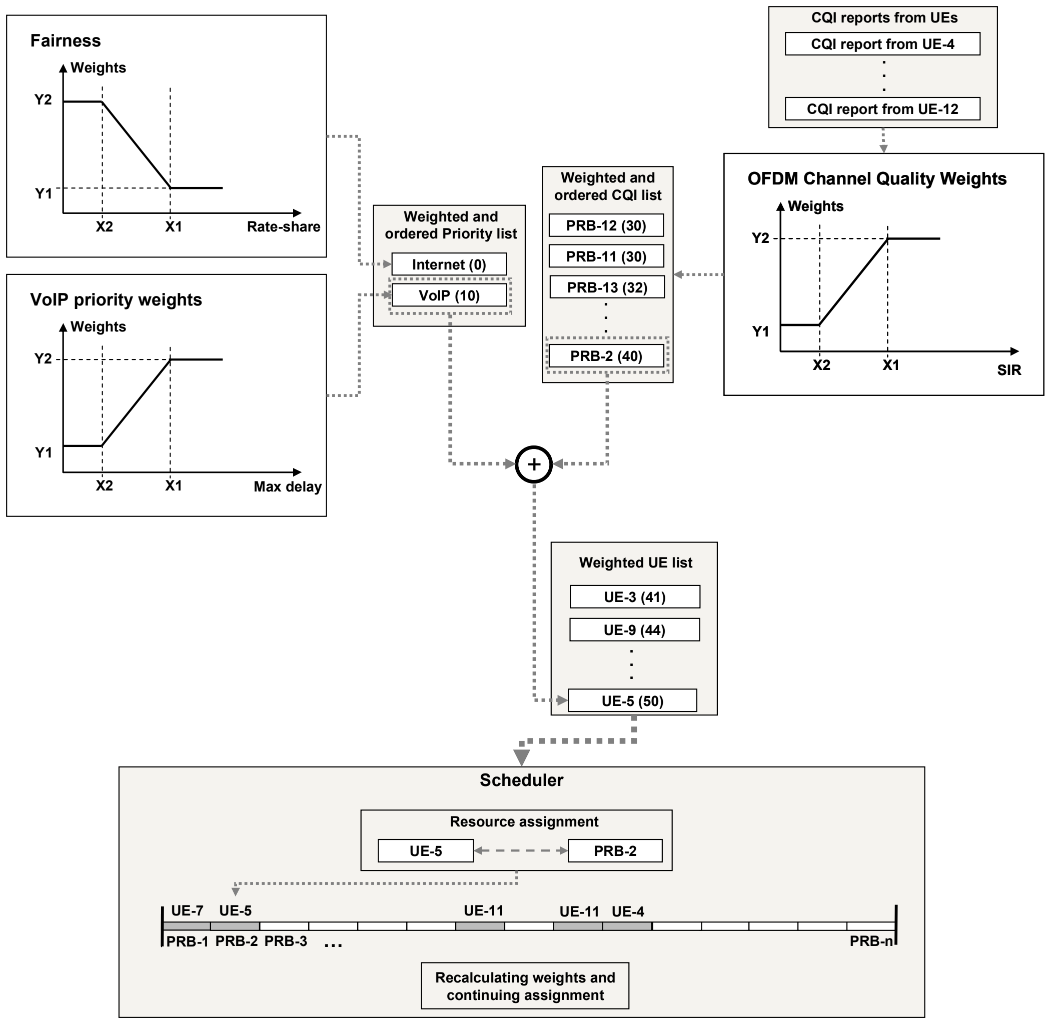


Figure 8: Functioning of the scheduler

The number of input parameters that the scheduler must take into account is quite large: channel quality, priority of services, queuing delays, fairness, etc. Assuming that there are a large number of users and resource blocks per cell, the computing consumptions of these inputs is very high and the available time is relative short (*TTI* is only one millisecond). In addition, the scheduler must know the scheduling history as well, because from the history it is able to determine which user should be prioritized in the next scheduling interval to ensure the fairness criteria. This means that for example, there is a good reason for a user to be scheduled when it has old *VoIP* frames in its queue, good channel quality and it got few radio block assignments in the past compared to other users. In order to achieve this behavior, a weight value is determined by the scheduler to each user taking all the mentioned parameters into account. Then the scheduler assigns the *PRBs* to the users in descending order of their weights.

Finally I summarize the above mentioned functioning of the radio resource assignment scheme in the investigated mobile network. The scheduler is the central element that has a large number of input parameter such as channel quality, service priority or fairness, and it attempts to assign the available resources to the most suitable users from a large number of users, in order to satisfy the requirements, such as high system capacity or service priorities. The scheduler must do its work as little processing power as possible because of the tight time interval of *TTI*.

3.3 Power allocation and link adaptation

Link adaptation is also applied in *LTE*. It is responsible for selecting the adequate modulation and coding schemes to the condition on the radio link. In *LTE* the radio link can employ *QPSK* for noisy channels, *QAM-16* and *QAM-64* for clearer channels. The *QPSK* is more robust and can tolerate higher level of interference but has lower transmission bit rate. *QAM-64* is most prone to errors due to interference, but it has three times larger bit rate than *QPSK*. The link adaptation adapts the modulation and coding scheme (*MCS*) according to the quality of the radio channel, thus it can adapt the bit rate and robustness of the transmission as well. In addition, it adapts the transmission power of the transmitter in order to minimize the interference caused by co-channels. The phenomenon is referred to as power control or power allocation. This scheme ensures that the mobile with good channel quality uses as much transmission power as necessary within the predefined maximum power to transmit its data. This means that the transmission power of a user is adapted to the desired *SIR* target and it is also limited in a *TTI*. The mobiles close to a base station transmit using very low level of transmission power. As they get further away they increase the transmission power as needed. Before a mobile user is scheduled the scheduler checks whether the user has more transmission power or not. In addition, not only the transmission power for a user is constricted, but the maximum power that can be used on a *PRB* by a user is also limited. These constraints are important from the generated interference point of view as well.

The use of power control also creates the potential for optimizing the inter-cell interference by exploiting that users closer to the base station transmit lower power and thereby generate lower level of interference which enable tighter reuse for the respective *PRBs*. Users closer to the cell edge can reuse *PRBs* with a large reuse distance. This creates the potential for optimization by using different reuse level depending on the partitions of the particular cell.

Thus, the benefits of the power control are that the level of interference can be reduced significantly and it increases the battery life of the mobile terminal as well. The power allocation scheme tries to increase the *SIR* in the system by measuring the received power and adjusting (decreasing or increasing) the transmitting power in order to maximize the minimum level of *SIR* in the entire system. The power control scheme is also described in subsection 2.4.

4. The proposed ICIC algorithm

The topic of this section is the presentation of the investigated problem and the detailed description of the proposed *ICIC* algorithm that takes the inter-cell interference into account in order to achieve improvement in bit rate. The algorithm attempts to reduce interference by coordinating the radio resource assignment in adjacent cells. Five variants of the proposed algorithm are introduced in detail.

4.1 Description of the problem

In the LTE system 1-reuse is used, hence the whole bandwidth can be used in each cell. In this concept each cell generates interference to other cells, hence attempts to reduce the interference in the system play a very important role. The investigation has been made only in uplink but the principle of the proposed algorithm works for downlink and uplink as well. The reason why only the uplink was analyzed is that in uplink power control is applied in the investigated mobile system. The lack of power control in downlink results in that there is less gain in terms of improvement in channel capacity using inter-cell interference coordination algorithm, because the base station uses the same (maximum) level of power for the transmission, hence generates the same level of interference, independently of the position of the mobile user [13].

Other important comment regarding uplink is that Single Carrier Frequency Division Multiple Access (*SC-FDMA*) is used in uplink instead of *OFDM* [11]. The reason for that is the *SC-FDMA* has lower Peak-to-Average Power Ratio (*PAPR*) and hence the transmit power of the mobile user is lower, which results in lower battery consumption than in case of *OFDM*. This scheme is similar to *OFDM*. It has only some small constraints compared to *OFDM*, such as the *PRBs* used by a user must be adjacent to each other. This means that there is no unused *PRB* between any two used ones allocated for the same user. The proposed algorithm takes these constraints into account as well.

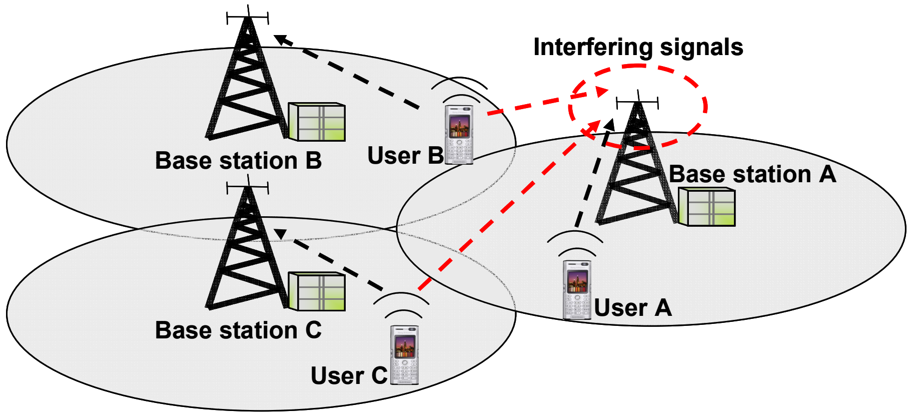
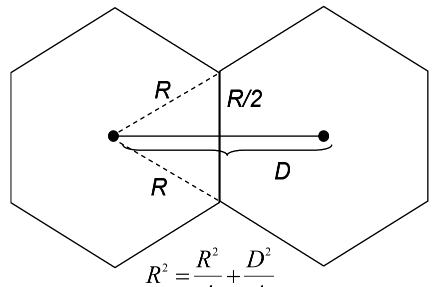


Figure 9: Problem illustration

The illustration of the problem in uplink can be seen in Figure 9. The transmission of *User A* is interfered at *Base station A* by the transmissions of *User B* and *User C* in the adjacent cells, because they use the same *PRB*. The high level of interference reduces the achieved *SIR*. That is, the achieved user bit rates decrease as well. Therefore, a solution that could reduce the caused interference would result in more efficient use of radio resource and thereby it would provide higher user bit rate as well as system capacity.

My task was to propose a radio resource reservation algorithm that reduces the interference between neighboring cells. The solution to the problem is referred to as Inter-Cell Interference Coordination (*ICIC*). The proposed algorithm tries to minimize the communication between base stations as well and another important aspect was that it must be integrated into the existing scheduling concept.

Compared to channel allocation schemes described in section 2, we can say that in Long Term Evolution the *co-channel reuse distance* is one, because in every neighbor cell the whole radio spectrum is available without any limitation. The co-channel reuse distance can also be calculated from (3) using the introduced denotations in section 2 where $D = \sqrt{3}\,R$ as it is illustrated in Figure 10.



$$R^2 = \frac{R^2}{4} + \frac{D^2}{4}$$

$$D = \sqrt{3}R$$

Figure 10: 1-reuse of frequency

As it was mentioned in section 2, signal-to-interference ratio is defined by (1), where it can be seen that the level of *SIR* depends on the distance between two stations using the same channel, here the channel represents the resource block. Therefore, in case of 1-reuse the generated level of interference is obviously higher, that is, the value of *SIR* is lower than for example, in case of 3-reuse. However, the achieved bit rate is lower in a system using 3-reuse due to reduction in the available frequency band. There is a trade-off between frequency reuse and achieved system capacity. The tighter reuse of frequency increases the available bandwidth in a cell that is a *gain* factor in the system capacity. However, the tighter reuse also decreases the signal-to-interference ratio due to higher level of interference caused by users that are closer to each other and use the same *PRBs*, which brings a *loss* factor in the system capacity.

In theory, it can be calculated which level of reuse results in the *gain* > *loss* case in terms of system capacity using Shannon channel capacity model. For example, the comparison in uplink channel capacity using 1-reuse and 3-reuse of frequency can be determined using Shannon curve, as it can be seen on the following figure. Figure 11 shows the achievable capacity per unit bandwidth for the achieved signal-to-interference-and-noise ratio (*SINR*) in the 1-reuse and 3-reuse cases. N_0 denotes the environmental noise factor in the system.

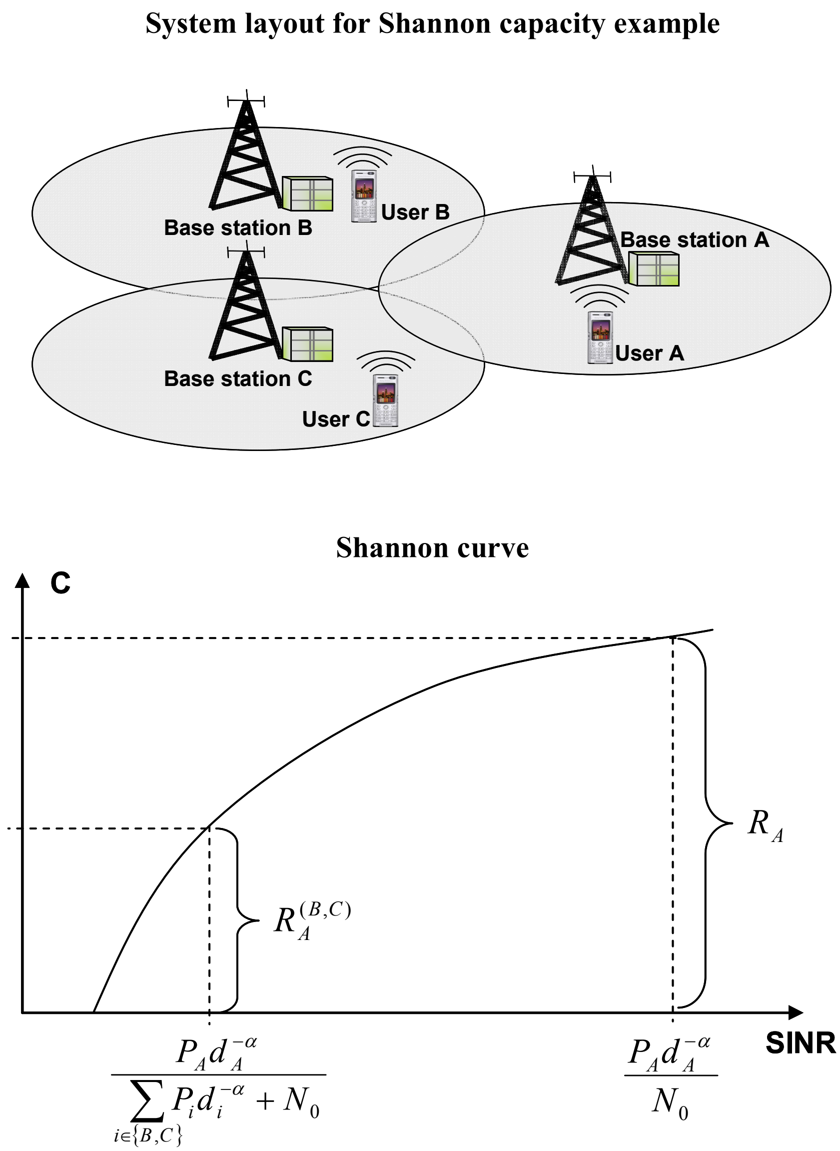


Figure 11: Shannon channel capacity

The notation is similar to the one used in section 2. Here P_A is the transmission power of *User A*, d_A is the distance between *User A* and *Base station A*. P_i, $i \in \{B,C\}$ denotes the transmission power of other base stations (*Base station B* and *C*) that cause interference for *User A*, and d_i is the distance between *Base station A* and the other two users (*User B* and *User C*). $R_A^{(B,C)}$ denotes the channel capacity when there is interference generated by the two neighbor cells in case of 1-reuse, and R_A is the channel capacity in case of 3-reuse of frequency, which means that there is no interference at all, because the frequency band is divided into 3 disjoint parts and each cell uses different frequency. The 3-reuse gives improvement in channel capacity if $\frac{1}{3}R_A > R_A^{(B,C)}$ condition occurs. The factor $\frac{1}{3}$ accounts for the capacity loss due to frequency partitioning in case of 3-reuse. This principle is also used in the proposed algorithm described in the following subsections.

4.2 Proposed algorithm

Five variants of the *ICIC* algorithm were developed. First I start by introducing the baseline version of the algorithm. The variants differ in selecting mobile users to be scheduled in a given *TTI*.

The three variants of the algorithm have the following principles. It differentiates two set of users, interior and exterior ones, depending on the differences between measured path gain to own and other cells. The differentiation is similar to reuse partitioning described in section 2.2. In practice, the cell is divided into two partitions, but here these partitions are defined by the radio position (measured path gain to base station) of the users. If the minimal value of these differences exceeds a predefined parameter value referred to as *geometry gain threshold* then the user is called interior, otherwise exterior. This classification of users results that the ones that are closer to their base station are interiors, because the path gain to the own base station is much greater than to any other neighboring base stations. The users that are far from their base station, called cell edge users, are exteriors, because they can measure higher path gain values to neighboring base stations and lower ones to own base station, which results in that the minimal difference between these values is below the given geometry gain threshold parameter.

This means that the interior users cause less interference to the mobile users that use the same *PRB* in the adjacent cells than the exterior ones. In other words, it is assumed that two exterior users scheduled on the same *PRB* in neighbor cell cause excessive interference to each other, hence the allocation of the same *PRB* to two exterior users in adjacent cells should be avoided by the scheduler. If two interior users or an exterior and an interior one use the same *PRB* in adjacent cell then they do not cause excessive interference. Excessive interference means that 3-reuse gives higher channel capacity than 1-reuse that is the *gain* from *SIR* is higher than the *loss* using 3-reuse. In general, this case occurs to cell edge users that are exteriors, hence the avoidance of using the same *PRB* for exterior users is beneficial in terms of system capacity. The objective of all variants of the proposed algorithm is to avoid cases when at least two exterior users use the same *PRB* (called exterior-exterior collision) in adjacent cells.

The proposed algorithm uses the above introduced principle as well. In the following subsections the presentation of the proposed *ICIC* algorithm and its variants can be found.

4.2.1 ICIC Start-Stop Index (baseline) algorithm

The functioning of the baseline algorithm is described in this subsection. As it was mentioned above, two groups of users are differentiated, interior and exterior users. The set of *PRBs* is divided into disjoint subsets and each cell is assigned to one of the subsets to be used for scheduling exterior users. For example, if the set of *PRBs* is divided into 3 disjoint sets then it means that 3-reuse is used for exterior users and 1-reuse for interior users as it can be seen in Figure 12. Figure 13 shows how the set of available *PRBs* used for exterior users is divided between cells.

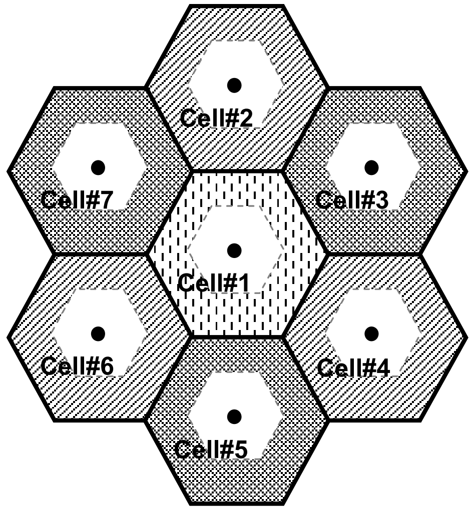


Figure 12: Assigning disjoint subsets of *PRBs* to cells using *ICIC* algorithm

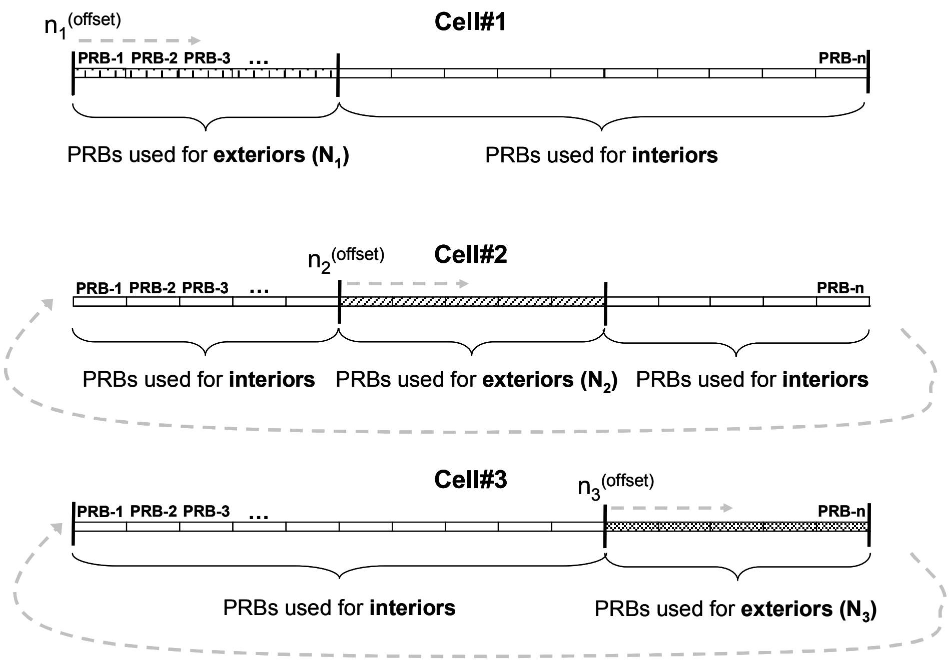


Figure 13: Division of *PRBs* used for exterior users between neighbor cells with *ICIC Start-Stop Index* algorithm

As we can see in Figure 13, the scheduler in *Cell#1* starts scheduling exterior users using the *PRB* having n_1 index (called start index or offset), then another neighbor scheduler in *Cell#2* starts scheduling exterior user using the *PRB* having n_2 index and the third neighbor one in *Cell#3* uses the *PRB* with n_3 index. Thus, the algorithm assigns an offset to each scheduler of the cells, which defines the index from which the scheduler has to start scheduling exterior users. Similarly, a stop index can be used by each scheduler. If the index of the used *PRB* exceeds the stop index, then the scheduler does not schedule more exterior users in the given *TTI*. This means that only N_1, N_2 and N_3 *PRBs* are available for exteriors in the corresponding cells. The update time interval of the exterior and interior differentiation is determined by a random variable with arbitrary distribution.

A new scheduling algorithm is needed in order to achieve the above mentioned functioning. The existing scheduling algorithm does not make this functioning possible. If the users were scheduled according to the user weights determined by the *QoS* and fairness criteria then exterior and interior users would fill up the available *PRBs* in arbitrary order and not according to the assigned reuse allocation designated by the start and stop index.

In order to achieve the desired functioning of scheduling, a two phase scheduling algorithm was proposed. In the first phase the scheduler works as it worked before. It schedules users according to only the weighted user list determined by the *QoS* and fairness criteria. It starts assigning the *PRBs* to the mobile users without considering the start and stop index. In this phase we get the order of the scheduled user in the given *TTI*. Then in the second scheduling phase the scheduled users are reordered in such a way so that exterior users come first between the start and stop indexes, then come interiors. This functioning results in that the exterior users use different *PRBs* in each cell, thus the exterior-exterior collision are completely avoided. The two phase scheduling is demonstrated in Figure 14.

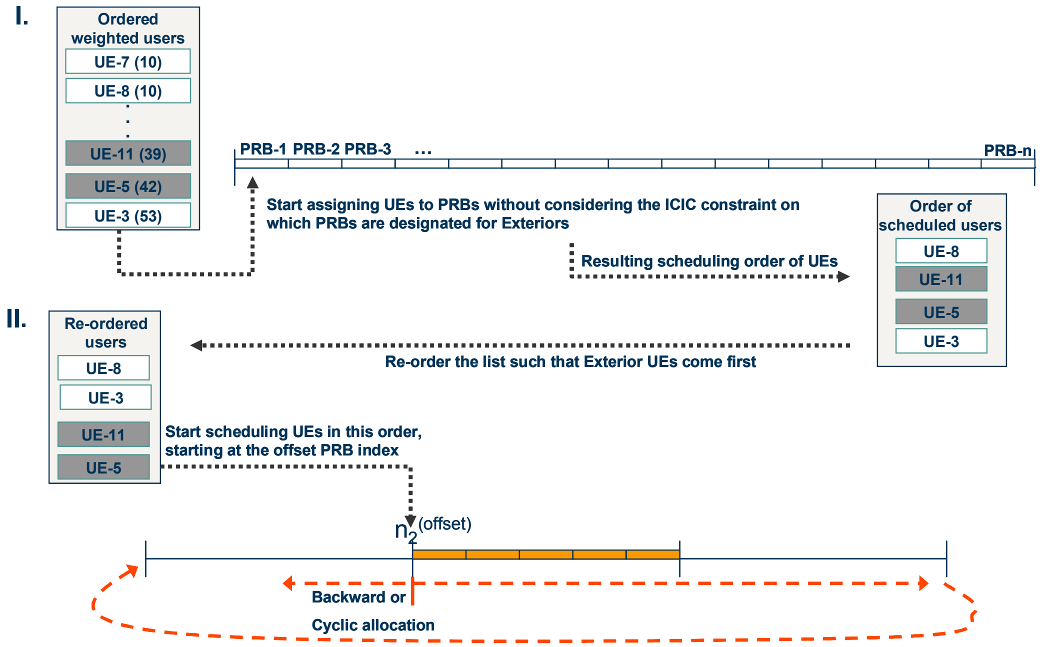


Figure 14: Two phase scheduling, example with *Cell#2* from Figure 12

The allocation is started with exteriors from the start index and then it is continued with interiors. In order to utilize the whole frequency band cyclic *PRB* allocation is allowed. This means that when the scheduler scheduled the *PRB* with the last index, it can continue assigning *PRBs* from the first index if it has not been used yet. The baseline variant is referred to as *ICIC Start-Stop Index* in the results of the simulation, in section 6.

The offset used by schedulers can be determined by frequency planning and can be configured from Operation and Maintenance (*O&M*). Depending on the number of base stations in the entire system a plan is used that determines which scheduler uses which offset for scheduling exterior users. In practice, this plan is represented in Figure 12 in case when 7 base stations are used in the system where the patterns show the different offsets. The offsets can be determined so that the number of the *PRBs* (N_1, N_2, N_3) used by exterior users are equal as it used in the baseline variant of the algorithm. This means that each cell has the same number of *PRBs* that can be assigned to exterior users.

In section 4.2.6, the sixth variant of the algorithm is mentioned at high level by giving ideas to the functioning where the offset is determined by the traffic load dynamically. This solution requires communication between adjacent base stations to negotiate the value of the offsets. This means that the network can configure itself adapting the current traffic load in the system. This variant has not been implemented and analyzed, but the proposal is presented for completeness.

4.2.2 ICIC Start Index algorithm

This variant is similar to the baseline version of the algorithm. It only differs from the baseline that the number of the allowed *PRBs* used by exterior users is not limited. In other words the stop index is omitted. As in case of the baseline version, the two phase scheduling algorithm is used. This means that in the second scheduling phase only rearrangement of the assignment is made. A possible example for *PRB* assignment using this variant is illustrated in Figure 15. Exterior users are prioritized then they are followed by interior ones as in the baseline case. This variant is referred to as *ICIC Start Index*.

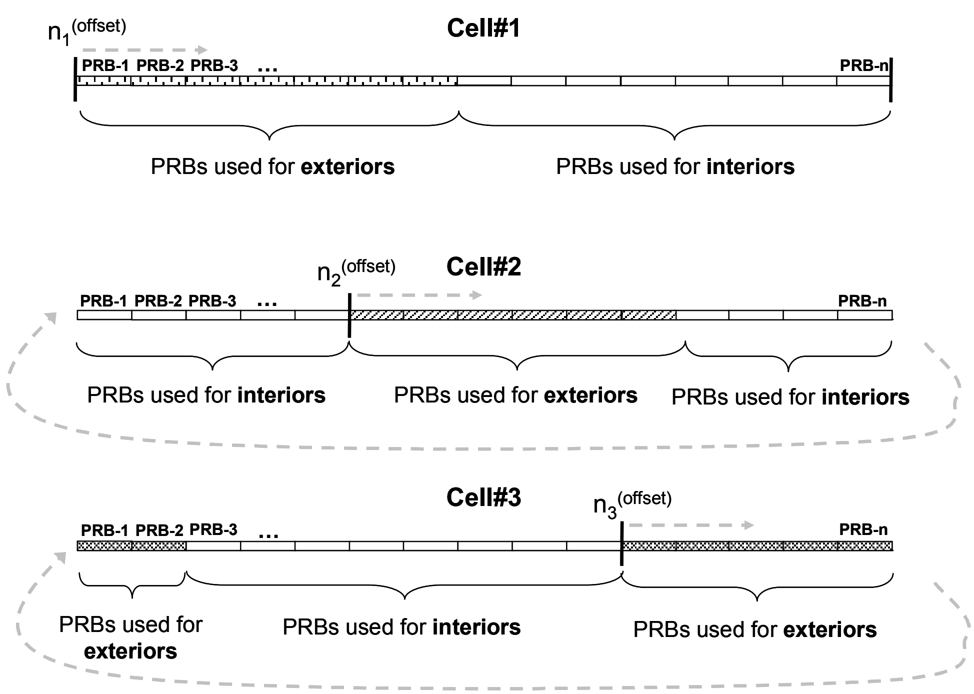


Figure 15: *PRB* assignment example with *ICIC Start Index*

4.2.3 ICIC Random Start Index algorithm

This version has the following changes compared to *ICIC Start Index*. The offset that determines from which *PRB* the scheduler has to start allocating exterior users is not set from a frequency plan but it is determined by a random variable with discrete uniform distribution. Another random variable with an arbitrary distribution describes how often in time this offset is reselected by the scheduler. This is necessary, due to the following possible situation. For example, if the schedulers in neighbor cells selected an offset close to each other and these offsets were not changed during the simulation then it would result in increased number of exterior-exterior *PRB* collisions, that is, loss in the improvement of the *ICIC* algorithm in terms of system capacity. This solution avoids the need for frequency planning.

Thus, every scheduler randomly selects an offset without taking the offsets of the neighbor schedulers into account. This version is called *ICIC Random Start Index* in the simulations. An example for *PRB* assignment with *ICIC Random Start Index* algorithm can be seen in Figure 16.

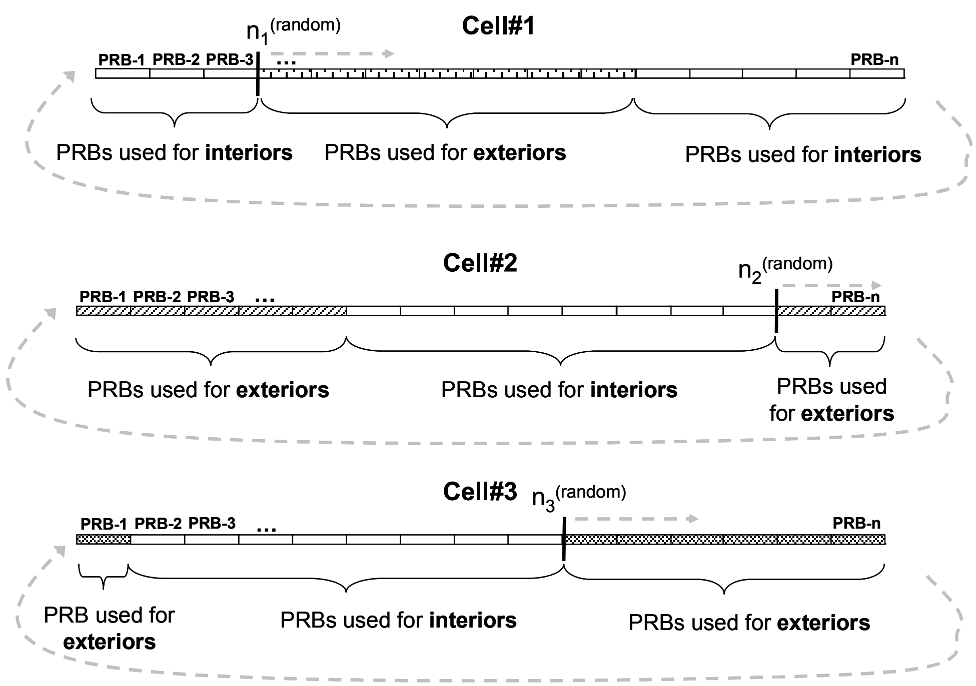


Figure 16: *PRB* assigning example with *ICIC Random Start Index*

4.2.4 ICIC Start Index Geometry Weight algorithm

The forth variant uses a different idea compared to the previous three ones. Instead of classifying mobile users into two groups, exteriors and interiors, this version gives more generalized classification of users. It measures the path gain between the mobile user and each base station. Let's denote *PG* the measured path gain value between mobile user and reference base station (where the mobile currently belongs to). The path gain value between mobile user and neighbor base station *i* is denoted with $PG^{(i)}$ determined for each neighbor base station. The algorithm maintains a sorted list in each cell in ascending order that contains $\min_{\forall i}\{PG - PG^{(i)}\}$ value (called geometry weight) determined for each mobile. This means that the first element of the list is such a mobile that can generate the largest interference with one of the neighbor mobiles in case when they use the same *PRB*. By assigning *PRBs* to a user from the top of the list the scheduler tries to avoid the collisions of the "most exterior" users. The first used *PRB* is determined by a predefined offset value (start index) in each cell as in case of the previous versions of the algorithm. These offsets are determined by frequency planning and can be configured from *O&M*. Then the next user that is assigned to the next unused *PRB* is the second one from the list, and so on. The scheduler continues assigning *PRBs* to mobiles using this principle. The idea behind this solution is similar to the idea of Simple Sorting Channel Assignment (described in subsection 2.2), but the proposed algorithm measures geometry weight instead of signal-to-interference ratio as in case of Simple Sorting and it coordinates the resource assignment by separating the *PRB* assignments of cell edge users in neighbor cells. Both schemes maintain a list based on measured values of geometry weight or signal-to-interference ratio. This version of the proposed algorithm is referred to as *ICIC Start Index Geometry Weight* and presented in Figure 17.

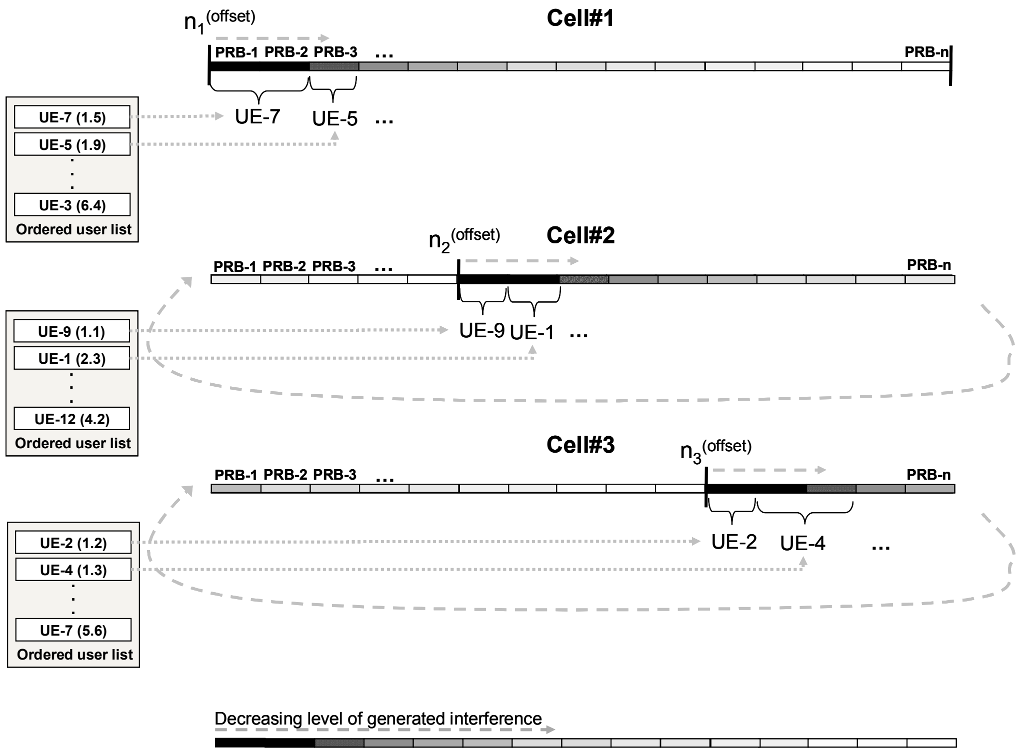


Figure 17: ***PRB*** **assigning example with** ***ICIC Start Index Geometry Weight***

The functioning of *ICIC Start Index Geometry Weight* results in that “most cell edge” users will use a different *PRB* than the ones in the adjacent cells.

4.2.5 ICIC Random Index Geometry Weight algorithm

The last developed and investigated version of the algorithm is a similar to *ICIC Start Index Geometry Weight* variant. The only difference is that the offset which determines the index of the first used *PRB* is selected by a random variable with discrete uniform distribution in each cell. The offsets are reselected by the scheduler from time to time as in case of *ICIC Random Start Index*. Therefore, this version can be seen as the combination of *ICIC Random Start Index* and *ICIC Start Index Geometry Weight* variants.

The significant advantage of this version is that frequency planning is avoided using random offset as in case of *ICIC Random Start Index* algorithm as well.

However, due to the randomness the gain using *ICIC Start Index Geometry Weight* algorithm is expected to be less than in case of frequency planning. This version is referred to as *ICIC Random Index Geometry Weight* and illustrated by Figure 18.

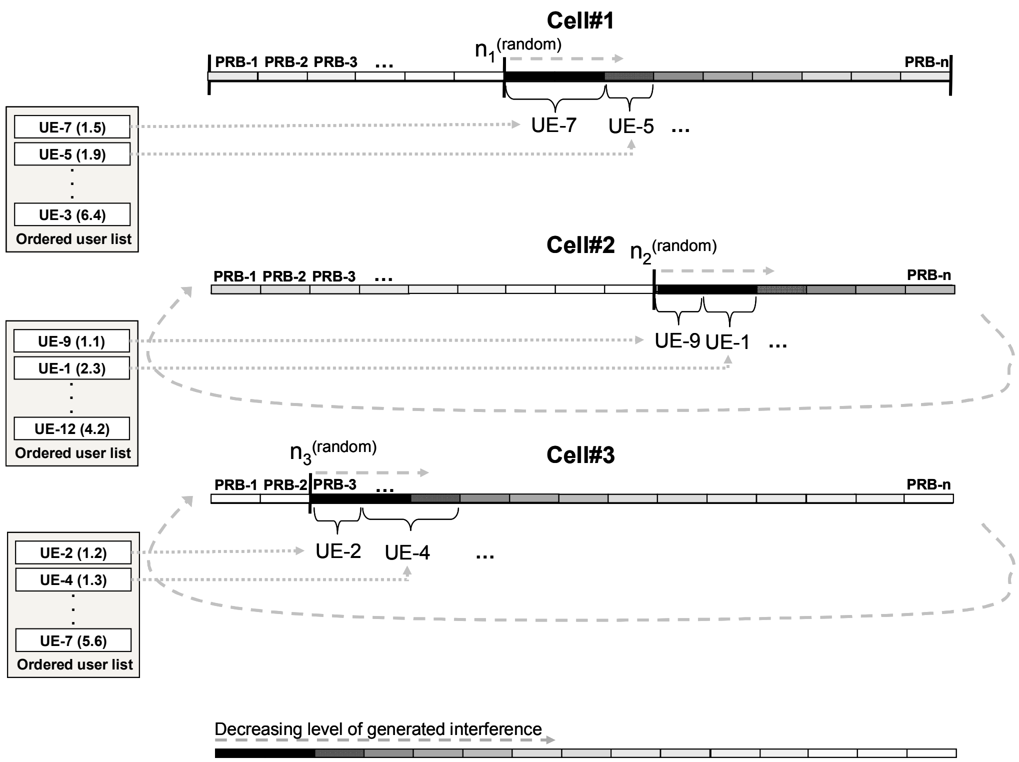


Figure 18: *PRB* assigning example with *ICIC Random Index Geometry Weight*

4.2.6 Traffic load dynamic ICIC algorithm

The above described algorithm variants are static solutions in the sense that they do not follow the traffic fluctuation with the *PRB* reuse pattern.

In this subsection I present the basic ideas for an algorithm which takes the traffic load of cells into account in order to achieve better improvement in system capacity as well as in user bit rates. This algorithm is not worked out in detail but a hint is given to the functioning of the algorithm. The scheme works in such a way so that it changes the available *PRBs* for exterior users in a cell dynamically depending on the own cell load and the *PRB* usage of neighbor cells. The initial setting is the same as in case of *ICIC Start-Stop Index*, that is, each cell has the same number of

PRBs available for exterior users. Then the start-stop indexes can be changed dynamically as the traffic load in the given cell changes. The base stations are able to measure the traffic load and the load of exterior and interior users as well. In addition, the base stations maintain a vector referred to as priority or allocation vector. The priority vector tells which *PRB* is prioritized for exterior users in a given cell. An example to priority vector in a given cell can be $\mathbf{P}_{\mathbf{cell\_A}}$ = [0,0,1,1,1,0,…0]. This means that the third, fourth and fifth *PRB* are used by an exterior user in a given period of time in the cell. Communication between base stations is assumed, hence the priority vectors can be exchanged regularly between neighbor cells. When a base station detects a high load of exterior users, it attempts to use more *PRBs* for exterior users such that it tries to increase the number of *PRBs* (N_i) used by exterior ones. If the next *PRB* after the last one which is used for exterior (stop index) is *free* then the base station sets 1 to its priority vector and starts using the *PRB* for exteriors. A *PRB* is called free if and only if it is not used by exteriors in any of the neighbor cells, that is the values of the priority vectors of neighbor cells are 0. If there is no such free *PRB* then the base station can ask its neighbor to try to shift their allocations upwards. An example for shifting allocations upwards can be seen in Figure 19.

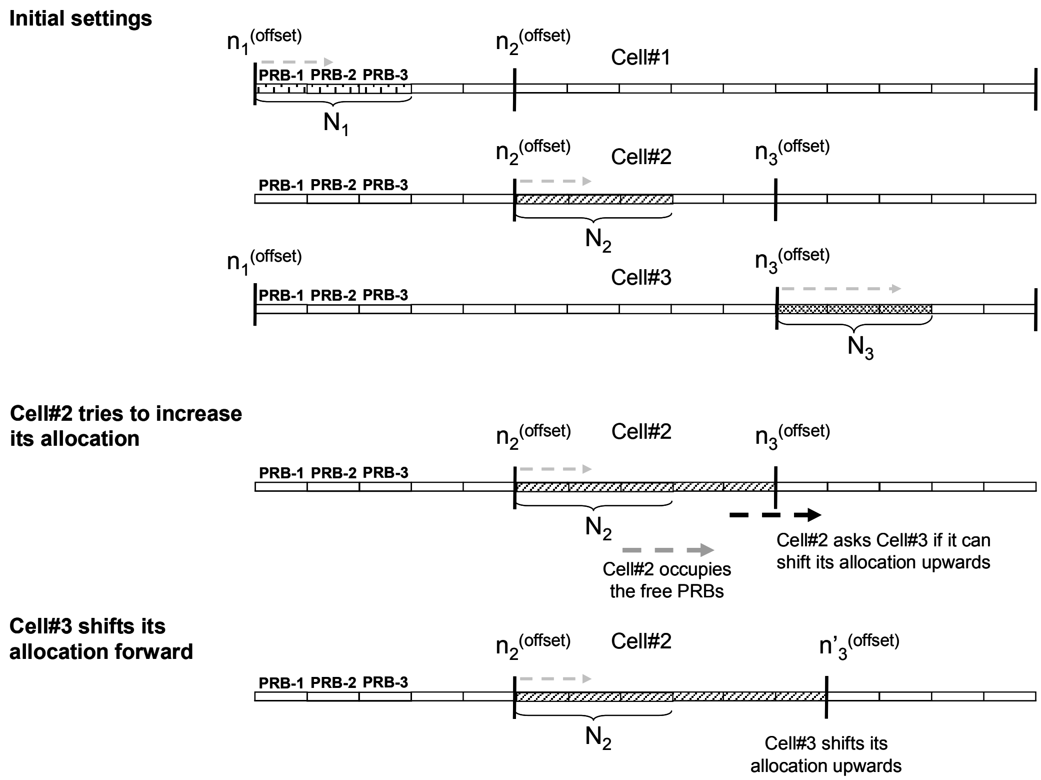


Figure 19: Allocation shifting example with *Dynamic Traffic Load ICIC algorithm*

The number of the shifted *PRBs* depends on the responses given by the asked neighbor base stations. When the traffic load decreases the base station that has more *PRB* used by exterior users than in the initial case, it releases some *PRB* by means of setting the corresponding value to 0 in its priority vector. Each base station tries to use its original offset if the corresponding *PRBs* are released. This solution assumes that the initial offset is determined by frequency planning and can be configured from *O&M*. It requires communication between base stations in order for the base station can ask *PRB* from its neighbor cells, therefore it is more complex solution compared to the static proposed and analyzed algorithm variants.

5. Simulation environment

The topic of this section is the brief introduction of the simulation environment and the extension of the simulator in order to evaluate the proposed algorithm variants. The implementation of the simulator extension is presented briefly in subsection 5.2.

5.1 Introduction of the simulation environment

To investigate cellular mobile systems the impacts of a large number of complex protocols and numerous stochastic processes have to be taken into account in order to analyze the efficiency of the entire system. It is a very common and sometimes the only solution to use simulations as a means to observe and analyze the functioning of telecommunication or computer networks. Therefore, the network simulators play very important role for engineers who want to study and develop a given complex network system. This is the reason why a simulator developed by Ericsson was chosen to analyze the behavior of the mobile system using the investigated algorithms. The topic of this subsection is the description of the used simulation environment.

The simulator is implemented in Java. It is an event based simulator which operates on discrete timeline. The simulator is able to simulate the protocols of the *TCP/IP* reference model. In addition, it handles a wide range of other network protocols and mechanisms regarding to mobile networks, such as Medium Access Control (*MAC*), Hybrid Automatic Repeat reQuest (*HARQ*) mechanism, Radio Link Control (*RLC*) implementing the second layer Automatic Repeat reQuest (*L2 ARQ*) technique, Robust Header Compression (*RoHC*) and Physical Layer (*PL*) on the radio interface, among others. The protocol layers and other network devices and functions are represented by corresponding modules in the simulation environment. The modules can be interconnected to each other by well defined functions depending on the desired investigated network.

One of the most important features of this simulator is that the radio link related tasks are implemented in detail, such as the small-scale propagation model, which is used to describe the rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance. Implemented small-scale propagation model is the multi path propagation. Implemented large-scale propagation effects are the shadowing and the distance dependent path loss component. These effects are used to describe the slow fluctuations of the radio signal. From the interference calculation point of view the modeling of these effects are important in the proposed algorithms as well. These models are used when the algorithm determines which mobile user is interior or exterior, or when it calculates the minimum path gain differences for the geometry weighted versions of the algorithm.

Using the radio channel of the simulator a large number of parameters can be adjusted both in uplink and downlink, such as the level of transmission power, frequency band, and number of *PRBs*, among others. Numerous modulation technologies have been implemented in the simulator, for example *OFDM*, *SC-FDMA* and *WCDMA* (Wideband Code Division Multiple Access). In the investigated network *OFDM* is used for downlink and *SC-FDMA* for uplink. The resources are divided in frequency and time, and assigned to users by the scheduler in each cell. The scheduling concept described in subsection 3.2 is also implemented in detail.

The wired physical transmission is modeled by physical transport channels. They are used on the transport network that interconnects the base stations of the system. The parameters for a transport channel are the bit rate, fix delay, loss probability, size of the buffer, and the queue management algorithm can be set as well.

In the investigated simulation environment the data link layer related tasks are done by *MAC* protocol that is responsible for the segmentation and reassembly of the data packet and ensures correct packet order transmission for the higher layer protocol. In the simulations it is used between the mobile terminal and the base station. Due to the significant packet loss on the radio interface, a fast error correction mechanism is used, referred to as *HARQ* mechanism, and on the top of that a second layer *ARQ* mechanism is applied.

As far as the higher protocol layers are concerned, they are also implemented in separate modules. An arbitrary protocol stack can be built up easily using these protocol entities that can be interconnected to each other very easily as well. In the application layer web, *VoIP* or streaming application can be used to generate data according to its parameter set.

5.2 Extension of the simulator environment

An extension for the existing simulator was implemented in order to ensure the interoperability with the proposed algorithms. Therefore, a wrap-around *PRB* assignment method was used in all algorithms to ensure that all *PRBs* are available for the scheduler independently of the offset where the assignment started. This means that after the last *PRB* is assigned to a user, the method tries to continue assigning with the *PRB* having the smallest index until it finds an unused *PRB* or there is no unused one at all. It was necessary in order for the algorithms to be able to utilize all *PRBs*. The wrap-around is represented by the arrows from the last *PRB* to the first one in the figures in subsection 4.2.

Then the two phase scheduling was added to simulator described in detail in subsection 4.2.1. This scheduling scheme enables to scheduler to rearrange the assignment of *PRBs* to users according to the functioning of the desired variant of the proposed algorithm.

In order for the simulation results reflect the real gain of the *ICIC* algorithms a new traffic model was implemented which contains a source and a sink entity. The source entity works as a data transmitter. It sends data with a given bit rate in every given period of time using a predefined data packet size without any acknowledgement of packets. The sink entity plays the role of the receiver that receives the data packet and drops them. The source entity sends data directly to *IP* layer. This means that the simulation results are not distorted, for example by a protocol functioning such as flow control, congestion avoidance or timeout effects in case of *TCP*.

Then a scheduler controller entity was introduced which is responsible for achieving the desired *ICIC* algorithm functioning in the simulation environment extended with the above mentioned features. This controller controls its scheduler according to the settings of its parameters. Each cell has a controller and the controllers are able to communicate to each other if it is necessary using an interface with predefined functions. The scheduler controller has several parameters that enable to be configured according to the conditions of the desired algorithm, such as the distribution of update time and the distribution of the offset used by the scheduler. The controller has to determine whether the user is interior or exterior, or calculates the sorted user list for *ICIC Start Index Geometry Weight* and *Random Index Geometry Weight* algorithms as well.

Using the described extension of the simulator all of the five variants of the *ICIC* algorithm were investigated and analyzed. The results of the investigation can be found in the next section (section 6).

6. Results of the simulations

Using the developed simulation environment a number of simulations were performed with various parameter settings and the results analyzed. In this section the parameter setting of the simulations, the results and their evaluation are presented. The parameter settings of the simulations are given by Table 1. It contains the values of all parameters that do not depend on the different variants of the *ICIC* algorithm.

Parameters	**Values**
Cellular layout	3 sites, 1 cell per site / 19 sites, 1 cell per site, Wrap-around
Inter-site distance	3464m (2000 m cell radius)
Distance-dependent path gain	-29.03 - 35.2log$_{10}$(R), R in meters
Bandwidth	5 MHz
Air interface	*SC-FDMA*
Number of *PRBs*	25
Total UE power	250 mW
UE maximum power per *PRB*	100 mW (power control is used)
Number of allowed *PRBs* per *TTI* per *UE*	2, 8, 16
Geometry gain threshold for exterior / interior classification	6 dB
Modulation	*QPSK, QAM-16* and *QAM-64*
Number of users	Between 1 and 30 per base station (on average)
Velocity of users	10 m/s
User distribution	Uniform
Traffic model	Rate limited infinite data source, full buffer

Table 1: Parameter settings for all simulations

The cellular layout tells how many base stations are on the simulation area and how many cells belong to one base station. Two scenarios were simulated, one with 3 base stations which was analyzed in detail and one with 19 base stations where only the throughput results were observed. The wrap-around technique is responsible for the user not to leave the simulation area in such a way so that when a user tries to leave the outmost cell the wrap around places the user on the opposite side of the simulation area without breaking its connection. The outmost cells are neighboring with the cells on the opposite side of the simulation area. In other words, the simulation area can be imagined as a surface of a sphere, whereon the user can move continuously in any direction.

The total *UE* power means the power that a user can use in a *TTI*. This is the sum of the power used on the *PRBs* assigned to a mobile. The number of allowed *PRB* per *TTI* per *UE* means that a user can use at most the given number of *PRBs* in one *TTI*. This constraint results in that the users in the system behave like narrowband users in order to avoid that one user fully utilizes the whole radio link capacity. The geometry gain threshold parameter is the used threshold value in case of *ICIC Start-Stop*, *Start* and *Random Start Index* algorithms in order to determine whether the user is exterior or interior. If the minimum value of the differences between measured path gain to own and other cells is below this threshold then the user is classified as exterior otherwise as interior. The geometry gain threshold was set to 6 dB according to [12].

Three different modulation schemes are used in the simulator for modulating the data of each user depending on the received level of *SIR* value. The number of transmitted bits per a modulation symbol depends on the *SIR* value and it is determined by the link adaptation function mentioned in subsection 3.3. The link adaptation selects the modulation where the bits per symbol value is the highest in order to achieve as high bit rates as possible.

The topics of the following two subsections are the presentation of the results and evaluations of different *ICIC* algorithm variants using a 3-cell system layout with different number of allowed *PRBs* per *TTI* per *UE*. Then the simulation results for the

19 base station cases are presented. The simulation results without inter-cell interference coordination are the reference point in the comparison.

6.1 Simulations results in 3-cell system layout

Using the 3-cell system layout numerous simulations were executed with different number of users in the whole system and different number of allowed *PRBs* per user per *TTI* in order to investigate the gain of the *ICIC* algorithms in terms of bit rate improvement at different traffic loads and with different type of users (narrowband, wideband). The movement of the users is uniform and the distribution of their starting positions is also uniform, which means that on average the number of users per base station is equal. First, the mean and the 5^{th} percentile of the user throughputs then the mean cell throughputs are presented in Figure 20, Figure 21, and Figure 22, respectively. The mean user throughput denotes the throughput averaged in time and for all users. The 5^{th} percentile throughput denotes the throughput value that on average the 95 percent of the users achieve. Figure 23 shows the main *SIR* values measured per *PRB* and they are averaged in time and for all users as well.

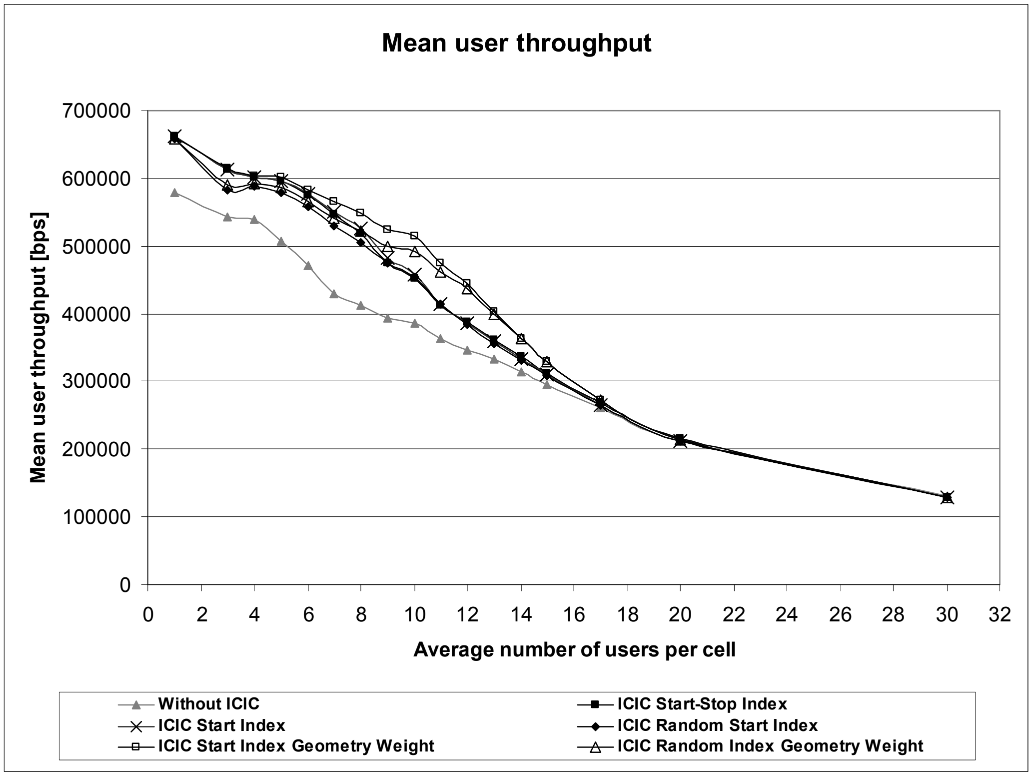


Figure 20: Mean user throughputs using *ICIC* algorithm variants with 2 allowed *PRBs*

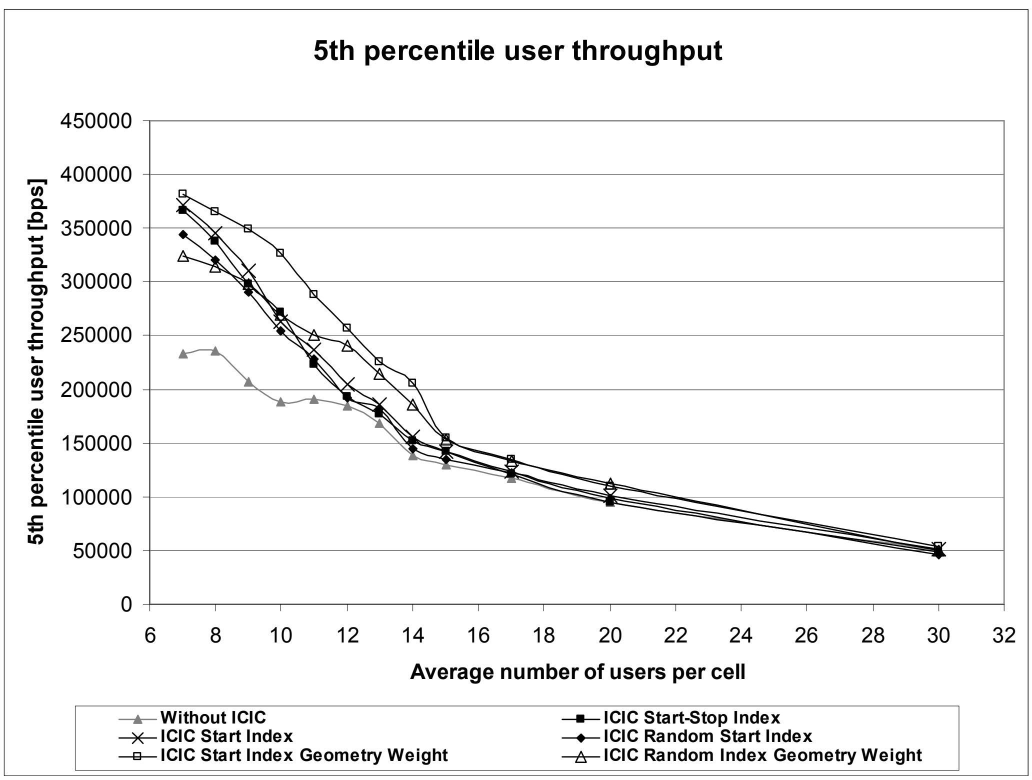


Figure 21: 5th percentile user throughputs using *ICIC* algorithm variants with 2 allowed *PRBs*

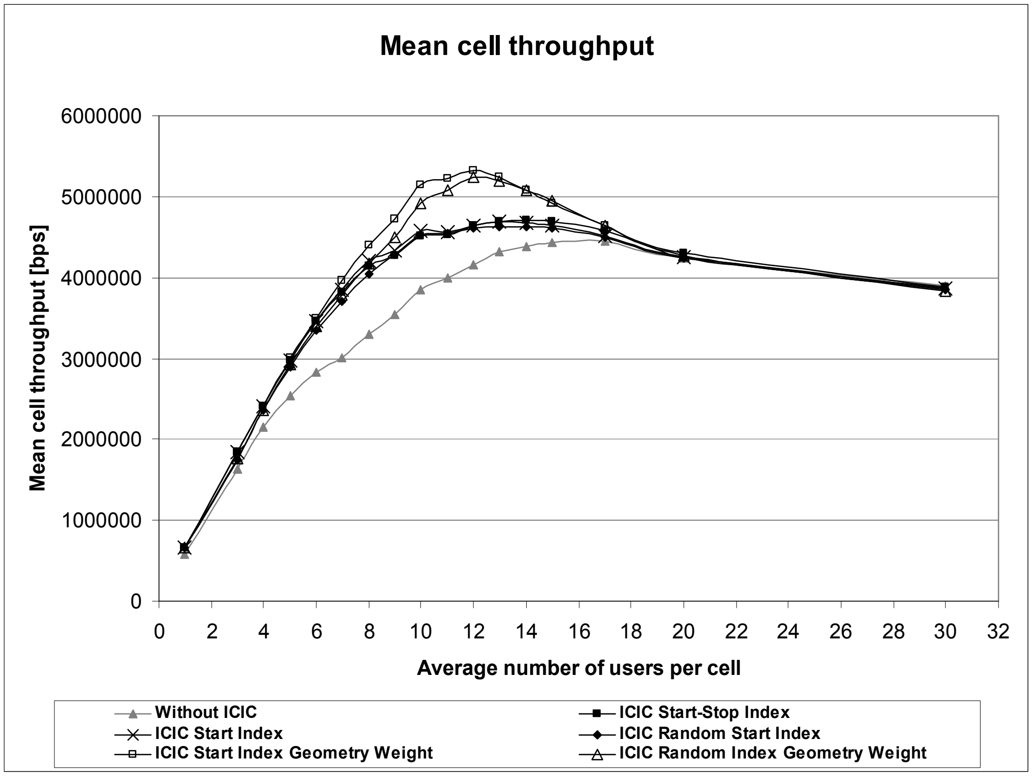


Figure 22: Mean cell throughputs using *ICIC* algorithm variants with 2 allowed *PRBs*

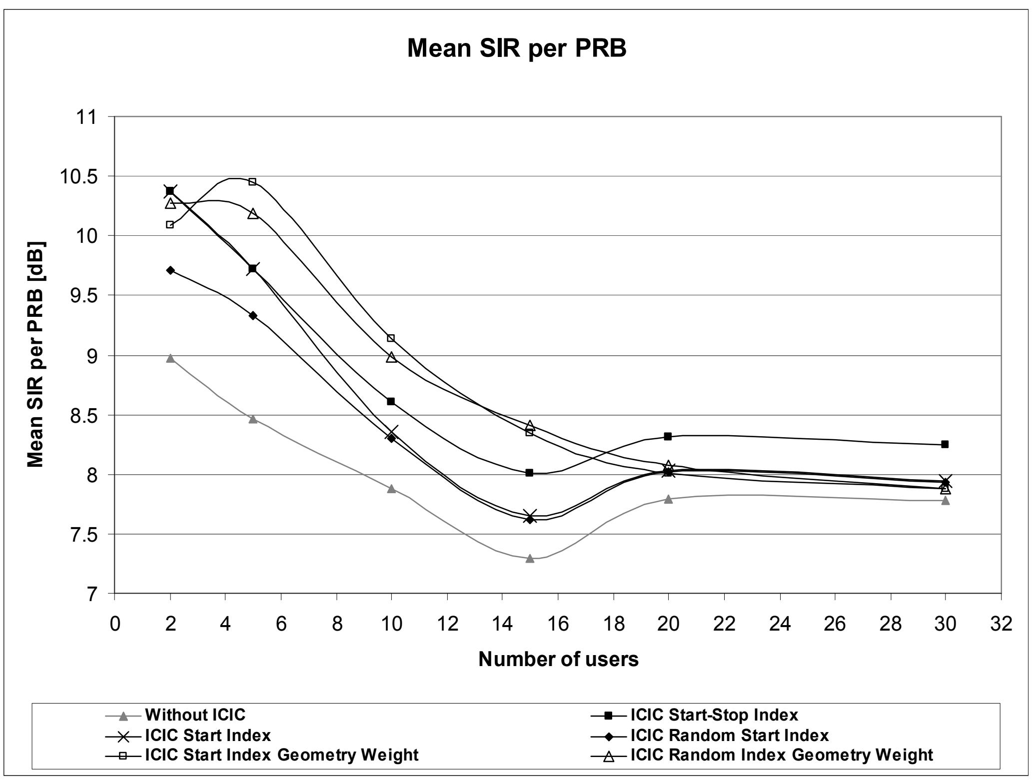


Figure 23: Signal-to-interference ratio per *PRB* using *ICIC* algorithm variants with 2 allowed *PRBs*

As it can be seen in Figure 20, as the load of the system increases the improvement in mean throughputs of the *ICIC* algorithm variants decreases. A user can use only two *PRBs* in a *TTI* and there are 25 *PRBs* in uplink according to Table 1, which means that about 13 users per base station are able to fill up all *PRBs*. Therefore, the full cell load belongs to the point where there are 13-15 users per base station. As we can see in the mean and in the 5th percentile user throughput figures the gain of the *ICIC* algorithm significantly decreases around these points. The reason of this phenomenon has been investigated and the result is presented at the end of this section. As Figure 20 shows the *ICIC* algorithms provide the largest gain at low and moderate cell loads, which results in about 20 percent improvement in the mean throughputs. However, the gain of *ICIC* algorithm disappears at full traffic load.

The investigation of the 5th percentile is very important, because in practice, it shows the achieved bit rates for cell edge users and as the 5th percentile figure (Figure 21) shows, the *ICIC* algorithms provide even higher improvement in the 5th percentile than in the mean user throughput.

As it was described in subsection 4.2.1, the *ICIC Start-Stop Index* variant ensures that the exterior users in adjacent cells use disjoint *PRBs*. The classification of users is updated in every second. The number of available *PRBs* was set to 25, hence in the 3-cell system the three start indexes were set to 0, 8 and 16, the stop indexes were 7, 15 and 24 according to the index of the cell. This means that for example, the scheduler of the second cell started scheduling exterior users using the *PRB* with index 8 and when the index of the used *PRB* reached 15 then the scheduler did not schedule more exterior users in that *TTI*. The start indexes were used in all of the frequency planned *ICIC* schemes (*Start-Stop Index, Start Index and Start Index Geometry Weight*) in the 3-cell system layout.

The mean user throughput figure is enlarged in Figure 24 focused on low and moderate traffic load in order for the differences to be observed easily. If we look at the two curves belong to *ICIC Start-Stop* and *ICIC Start Index*, we can observe only a small difference between them. At high traffic load both cases performs the same throughput values.

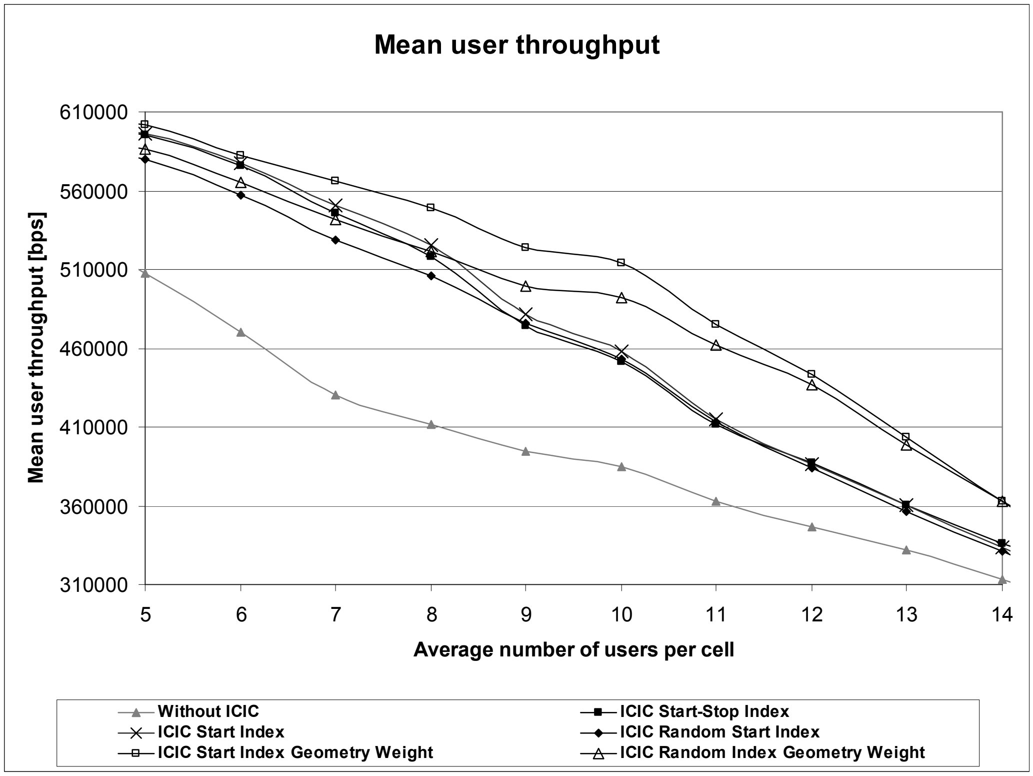


Figure 24: Mean user throughputs using *ICIC* algorithm with 2 allowed *PRBs* enlarged between 5 and 14 users per cell

As it was mentioned earlier, the advantage of using the randomized versions of the algorithm is that there is no need for frequency planning to assign all start indexes to schedulers in the entire system. We can also observe in Figure 24 that the difference in the achieved mean user throughput between frequency planned (*Start-Stop Index, Start Index and Start Index Geometry Weight*) and randomized (*Random Start Index and Random Index Geometry Weight*) *ICIC* schemes are not significant, which means that the avoidance of frequency planning does not have a high impact on the gains of the *ICIC* algorithm.

With the randomized variants of the *ICIC* algorithm, the start index is assigned to schedulers using a random variable with uniform distribution. Therefore, it is possible that the start indexes are close to each other which results in that the number of cases when two exterior users use the same *PRB* is larger. That is, the number of exterior-exterior *PRB* collision is higher. Note, that the new random numbers are redrawn for the start indexes every second in order to avoid that "unlucky" cells use the same start indexes constantly. The randomness can cause a little bit decreased improvement in bit rates compared to the frequency planned cases, but it is still significant compared to the case without *ICIC*. This means that the inter-cell interference coordination without frequency planning can be an attractive alternative even from the operator's point of view as it avoids the need for cumbersome frequency planning.

We can also observe in Figure 24 that the *ICIC Start Index Geometry Weight* provides the highest values of the mean user throughputs. This scheme uses certain path gain measurements (called geometry weight) in order to maintain a sorted list of mobile users. The scheduler schedules the user that may cause the highest interference, that is, the "most exterior" user in the neighbor cells starting from the predefined start index. This algorithm variant brings also the highest improvement in the 5th percentile, mean cell throughput and mean *SIR* per *PRB* values at low and moderate traffic load. Due to the generalized classification of users determined and maintained by the scheduler using the geometry weight, this variant can be expected to give the highest improvement on average in the system and user capacity as well, however these schemes are more complex than the ones using exterior-interior classification only.

Note, that if there are less than 7 users per base station, it is not possible to calculate or estimate a reasonable value of the 5th percentile user throughput due to the small number of users, hence the cases where there are less then 7 users on average per base station are not presented in the 5th percentile figures. In Figure 22 the mean cell throughput can be observed. The throughput values are averaged in time and for the three cells as well.

Figure 23 shows the achieved gain of the *ICIC* algorithm variants in terms of the increased signal-to-interference ratio. Significant difference can be observed using the *ICIC* schemes at low and moderate traffic load compared to the reference case, but the difference in the mean *SIR* values decreases as the load of the system increases. Important to note, that at high traffic load the improvement of the *ICIC* algorithm in signal-to-interference ratio is less than 0.5 dB, which does not result in significantly higher bit rate. The reason for this is that the modulation versus number of bits per symbol table contains discrete points as it can be seen in Figure 25. When a *SIR* value is determined using a *PRB* the simulator selects the nearest *SIR* value in the table and the corresponding bits per symbol value. The selected value is the same at high load with and without *ICIC* due to the small difference in *SIR*. The reason why the gain of the *ICIC* algorithm is only 0.5 dB is investigated in section 6.3.

The relation between the number of transmitted bits per symbol and the *SIR* value using different modulation schemes can be seen in Figure 25, where three different bits per symbol values belong to a given *SIR* value.

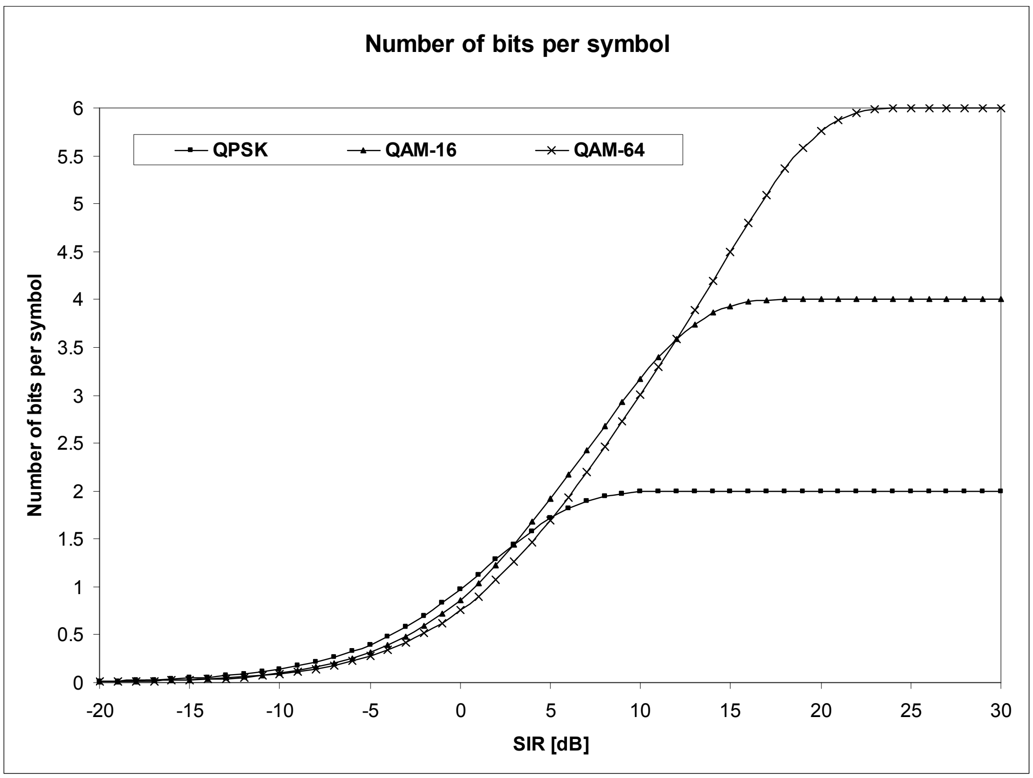


Figure 25: Signal-to-interference ratio versus number of bits per symbol using *QPSK*, *QAM-16* and *QAM-64* modulations

As Table 1 shows, the simulations were executed using different number of allowed *PRBs* for a user to use in a *TTI*. In the following paragraphs these simulation results are presented and discussed starting by the case when 8 *PRBs* were allowed for a user to use. First the mean and 5th percentile user throughput then the mean cell throughput are illustrated in the following figures.

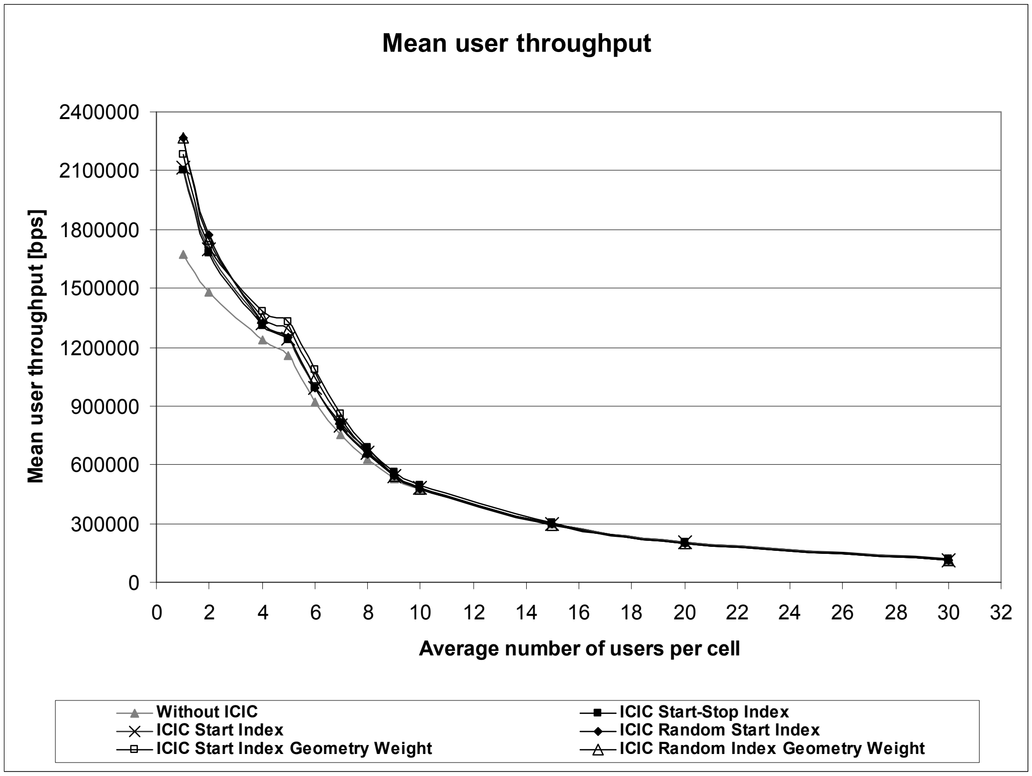


Figure 26: Mean user throughput using *ICIC* algorithm variants with 8 allowed *PRBs*

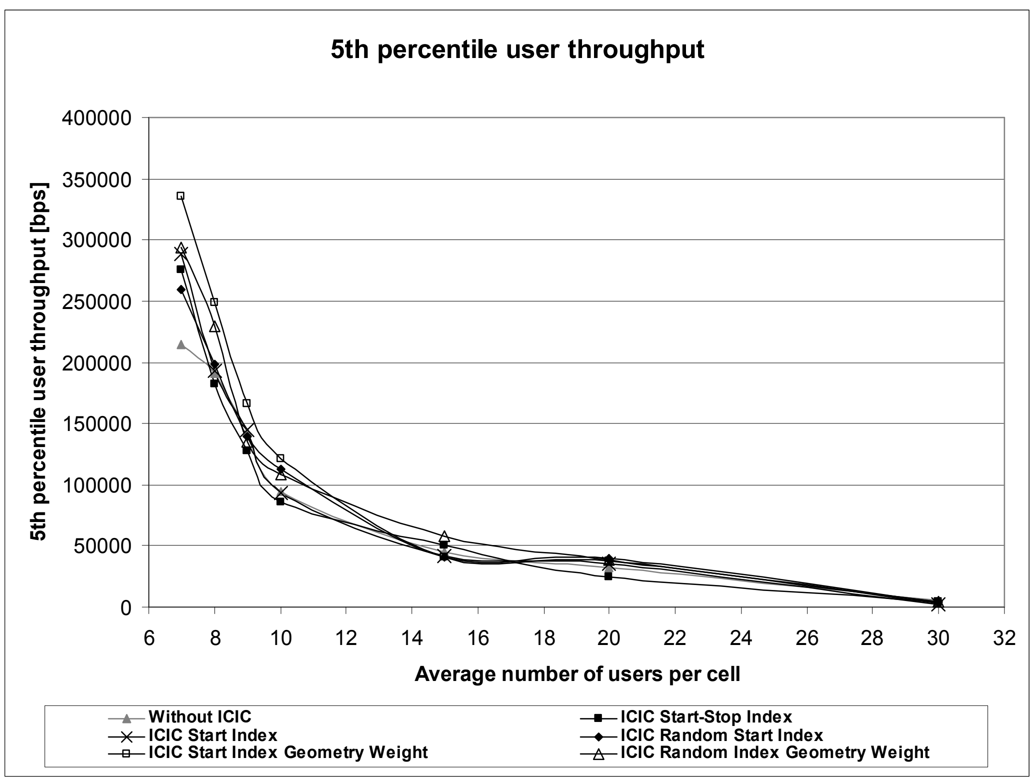


Figure 27: 5th percentile user throughput using *ICIC* algorithm variants with 8 allowed *PRBs*

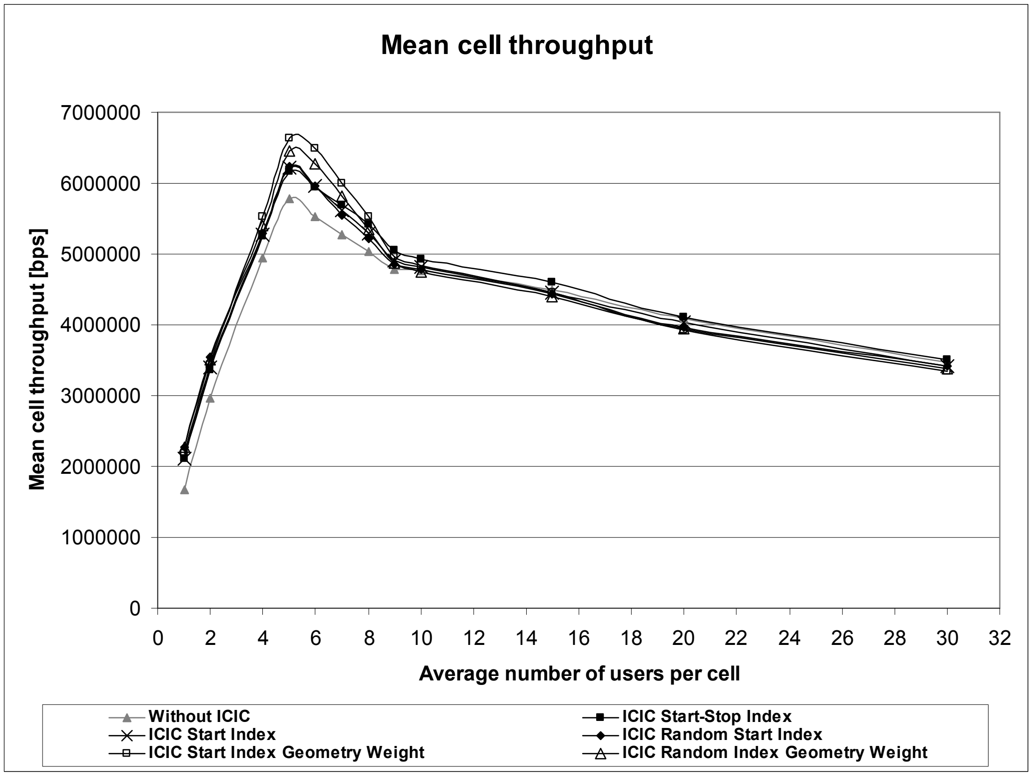


Figure 28: Mean cell throughput using *ICIC* algorithm variants with 8 allowed *PRBs*

We can observe in the previous throughput figures (Figure 26, Figure 27 and Figure 28) that the overall gain of *ICIC* algorithm is still significant, but some loss can be seen in the improvement compared to the case when only two *PRBs* were allowed to a mobile user per *TTI*. The following three figures show the throughputs values using *ICIC* algorithm with 16 allowed *PRBs* per user per *TTI*. This means that the users become more wideband compared to the previous cases.

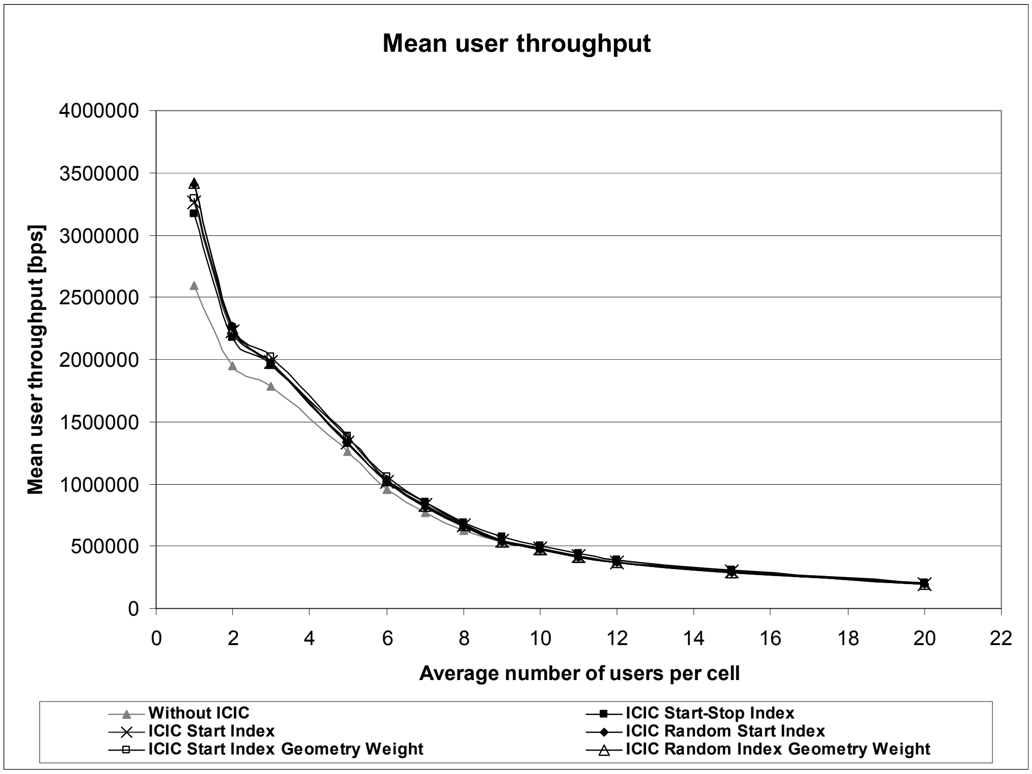


Figure 29: Mean cell throughput using *ICIC* algorithm variants with 16 allowed *PRBs*

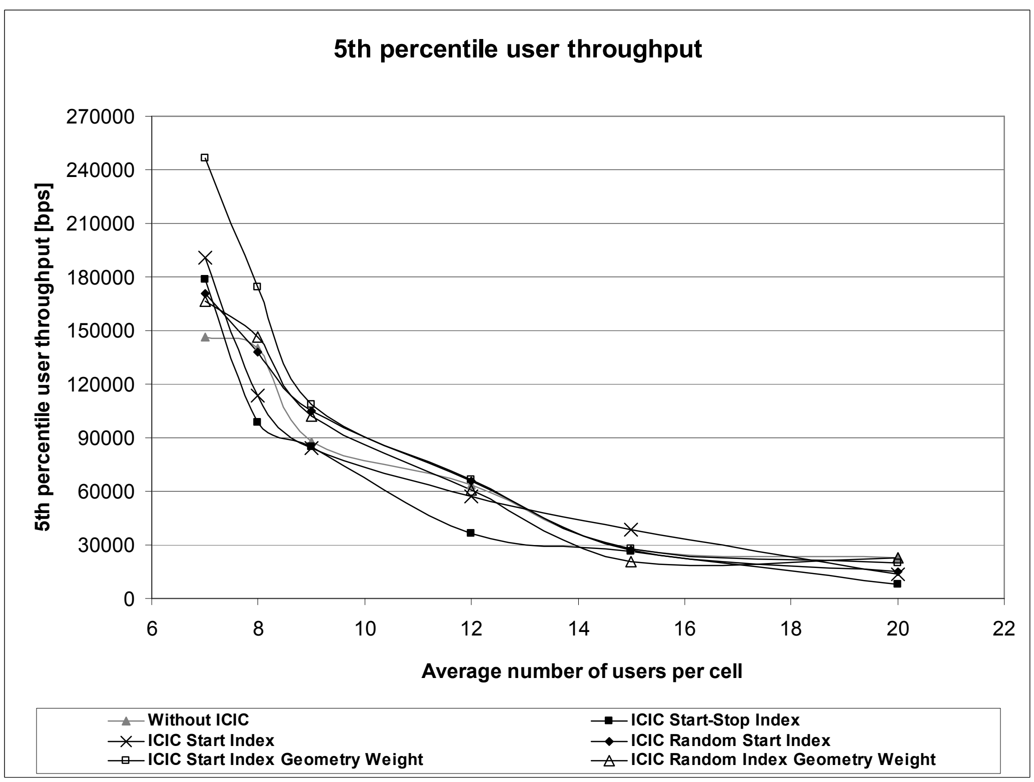


Figure 30: 5th percentile user throughput using *ICIC* algorithm variants with 16 allowed *PRBs*

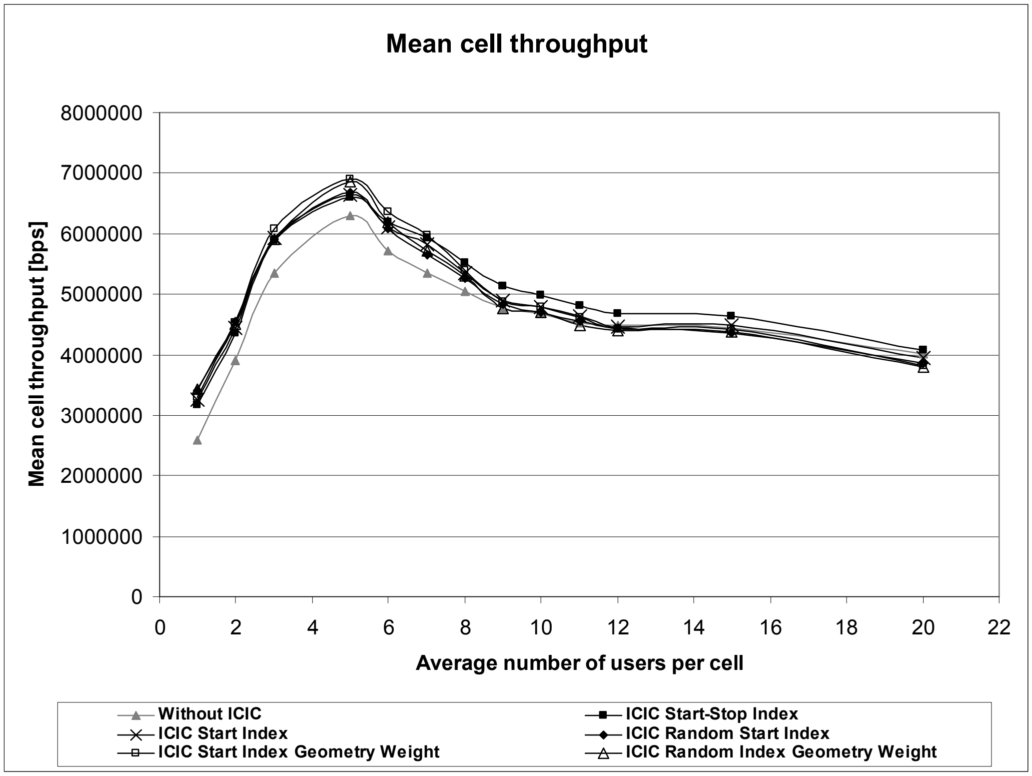


Figure 31: Mean cell throughput using *ICIC* algorithm variants with 16 allowed *PRBs*

The previous results show that the achieved throughput values using *ICIC* algorithm variants decreases as the number of the allowed *PRBs* per user per *TTI* value increases. That is, the gain of the inter-cell interference coordination decreases as the users are getting more and more wideband. The reason for this is that in case of wideband users the number of the scheduled users is lower compared to case with narrowband users which means that the scheduler starts working more and more "in time domain" instead of frequency one. This results in that the *ICIC* algorithm has lower "degree of freedom" in terms of the rearrangement of assignments of users. For example, if only three users are scheduled in a *TTI* in both cells using 8 *PRBs* for each user and two users are exterior then it results in that two users using the same *PRBs* in adjacent cells cause higher number of exterior-exterior collision using any of the *ICIC* algorithm, except *ICIC Start-Stop Index*. This variant stops scheduling exteriors after the stop index is reached, and thereby it schedules less number of exterior users compared to other cases, which results in that the 5th percentile user throughput values can be lower than the reference case at some points.

6.2 Simulation results in 19-cell system layout

The previous investigations were made in a 3-cell system layout. Therefore, the proposed *ICIC* algorithm variants were also investigated in a system containing 19 base stations. The following three figures show the obtained simulation results using two allowed *PRB* per user per *TTI*. These results can also be found in [13].

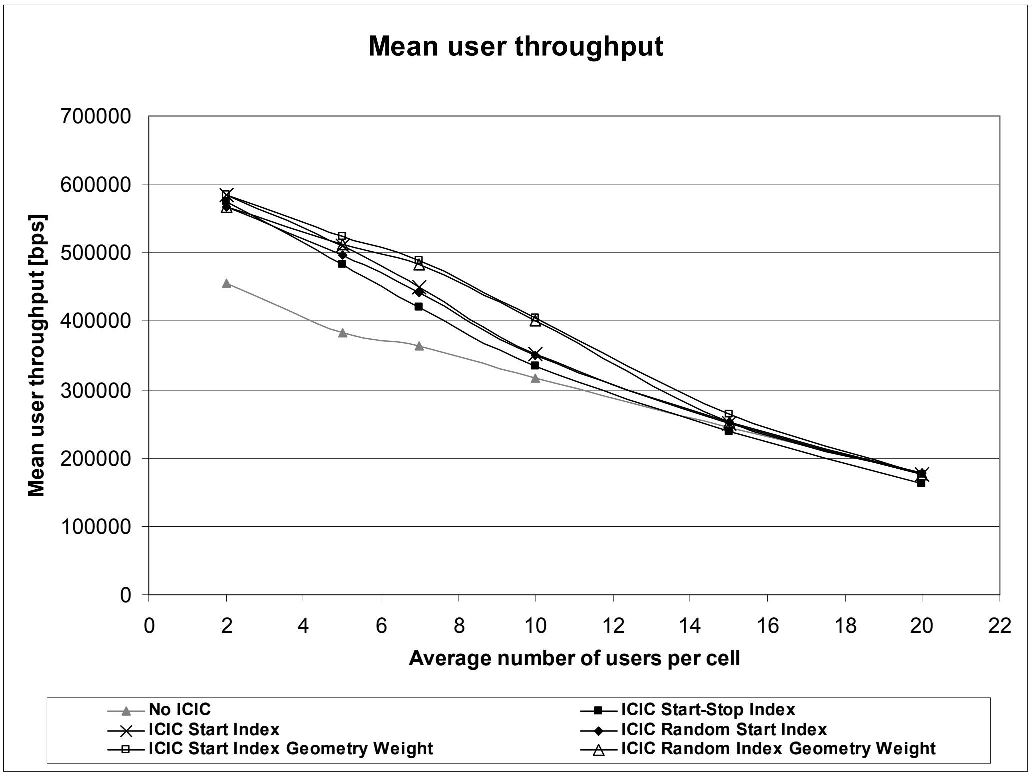


Figure 32: Mean user throughput using *ICIC* algorithm variants with 2 allowed *PRBs* (19-cell system layout)

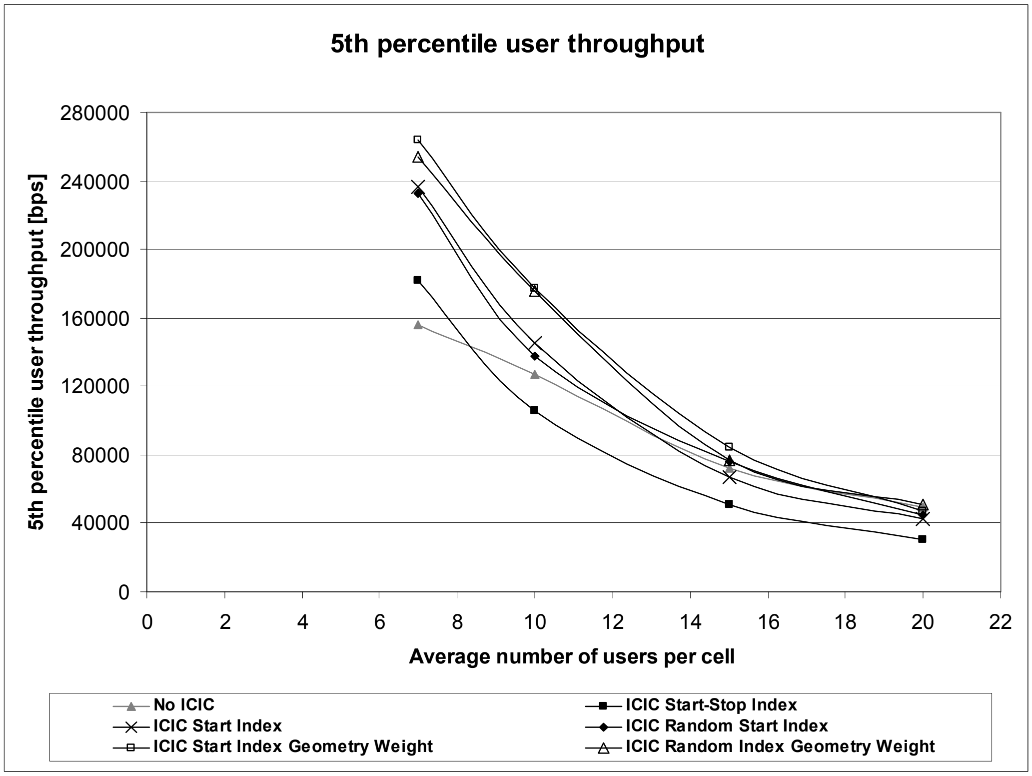


Figure 33: 5th percentile user throughput using *ICIC* algorithm variants with 2 allowed *PRBs* (19-cell system layout)

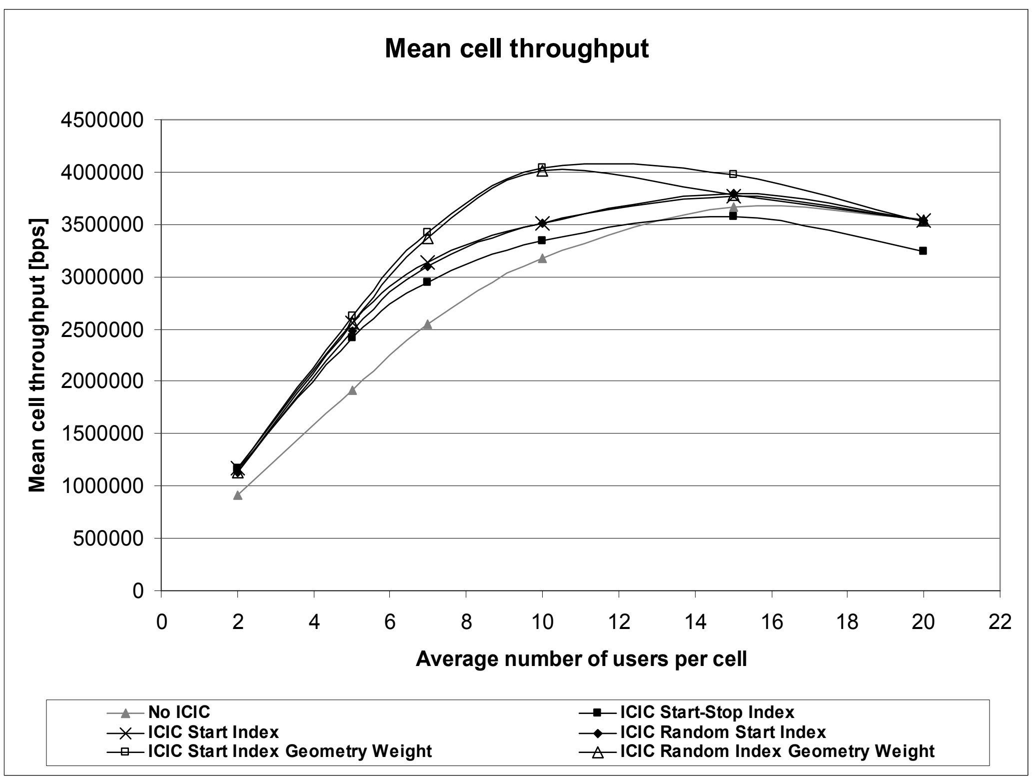


Figure 34: Mean cell throughput using *ICIC* algorithm variants with 2 allowed *PRBs* (19-cell system layout)

The simulation results are similar to the ones in the 3-cell system layout using two *PRBs* limitation for a user in a *TTI*. The absolute values of the obtained numbers in the throughput figures are lower than in case of the 3-cell system layout. The reason is that the level of the *SIR* value is higher in the entire system due to the higher number of transmitting users.

We can also observe that all of the mean cell throughput figures have an interesting shape. After they reach their maximum values, they start decreasing. The reason for this is that the scheduler wants to ensure fairness and it tries to schedule those users that have been received low bit rates, that is, the exterior users are scheduled mostly in a *TTI* and they can transmit fewer bits compared to interior users due to the lower level of achieved *SIR*. The uplink scheduler applied in the simulator does not take into account the channel quality (*CQI*) of the *PRB*, which would allow to balance between fairness and system throughput. In the next subsection the analysis of the high traffic load behavior of *ICIC* algorithms is presented in detail.

6.3 High traffic load analysis

An interesting question regarding to the presented simulation results is the reason why the gain of the *ICIC* algorithm disappears at high traffic load. In order to explain this phenomenon, some definitions must be introduced that are valid for the cases when exterior/interior classification is used (*ICIC Start-Stop*, *Start* and *Random Start Index*) in two adjacent cells (*Cell#1* and *Cell#2*). These definitions are the followings.

- The *SIR* achieved at the *exterior-exterior collision* denotes the measured *SIR* value when two exterior users use the same *PRB* in the adjacent cells.

- The *SIR* value of *exterior-interior collision* means *SIR* value measured by the exterior user in *Cell#1* that collides with an interior user in *Cell#2*.

- The *SIR* value of *interior-exterior collision* denotes the *SIR* value measured by the interior user in *Cell#1* that collides with an exterior user in *Cell#2*.

- The *SIR* of *interior-interior collision* means the achieved *SIR* value when two interior users use the same *PRB* in the neighbor cells.

At high traffic load all of the *PRBs* are filled up with users. This means that there is no unused *PRB*, that is, any of the *PRBs* collides to another *PRB*. Figure 35 shows an example to the collisions of *PRBs* at high traffic load in a *TTI* in two adjacent cells when *ICIC* algorithm is not used.

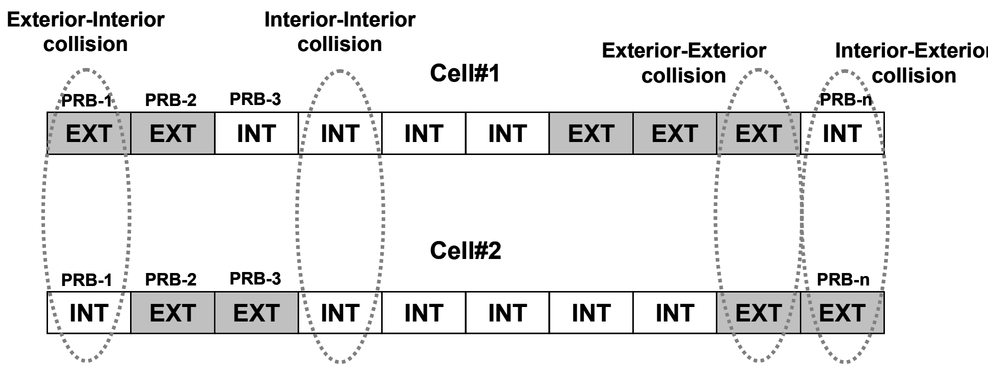


Figure 35: Example to the *PRB* collisions in two adjacent cells from the Cell#1 point of view

As it can be seen in Figure 35, all of the *PRBs* are filled up with interior or exterior users. Four kinds of collision occurred, exterior-exterior, exterior-interior interior-exterior and interior-interior collisions. If one of the *ICIC* algorithm variants, for example, the *ICIC Start Index* is used then the assignments of the scheduled users are rearranged as it is represented in Figure 36.

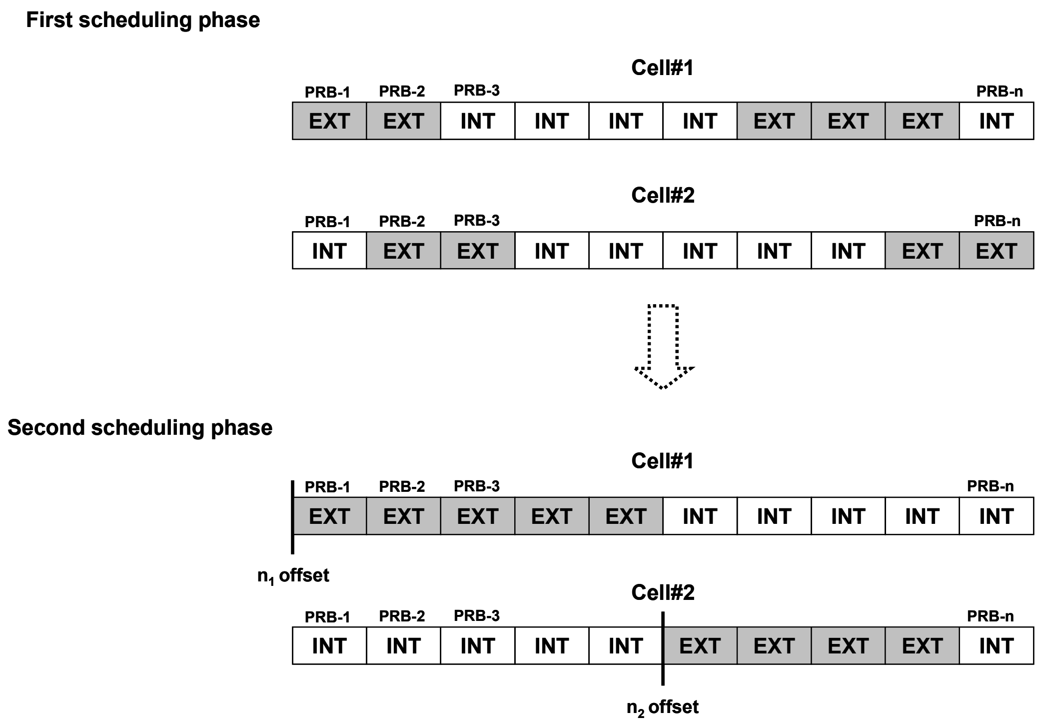


Figure 36: Example to the *PRB* collisions with the *PRB* assignment rearranged by *ICIC Start Index* algorithm

Let's denote $C_{ext\text{-}ext}$ the number of exterior-exterior collisions in the first scheduling phase which is two in the example illustrated by Figure 36. This figure also shows that in this case the *ICIC* algorithm dissolves $C_{ext\text{-}ext}$ number of exterior-exterior collisions in *Cell#1* and introduces $C_{ext\text{-}ext}$ number of exterior-interior collisions instead, that is, the exterior-exterior collisions are replaced by exterior-interior collisions which bring a *gain* factor in the system. However, this also means that the introduced $C_{ext\text{-}ext}$ number of exterior-interior collisions replaces the same number of interior-interior collisions. From *Cell#2* point of view it means that $C_{ext\text{-}ext}$ number of interior-interior collisions are replaced by interior-exterior collisions which bring a *loss* factor in the system. The introduced *gain* and *loss* factors, that is, the achieved *SIR* values in case of different collisions have been investigated and the result is shown by Figure 37. The figure shows the measured average *SIR* per *PRB* values for the four different combinations of collisions plotted out by the information bit versus *SIR* curves.

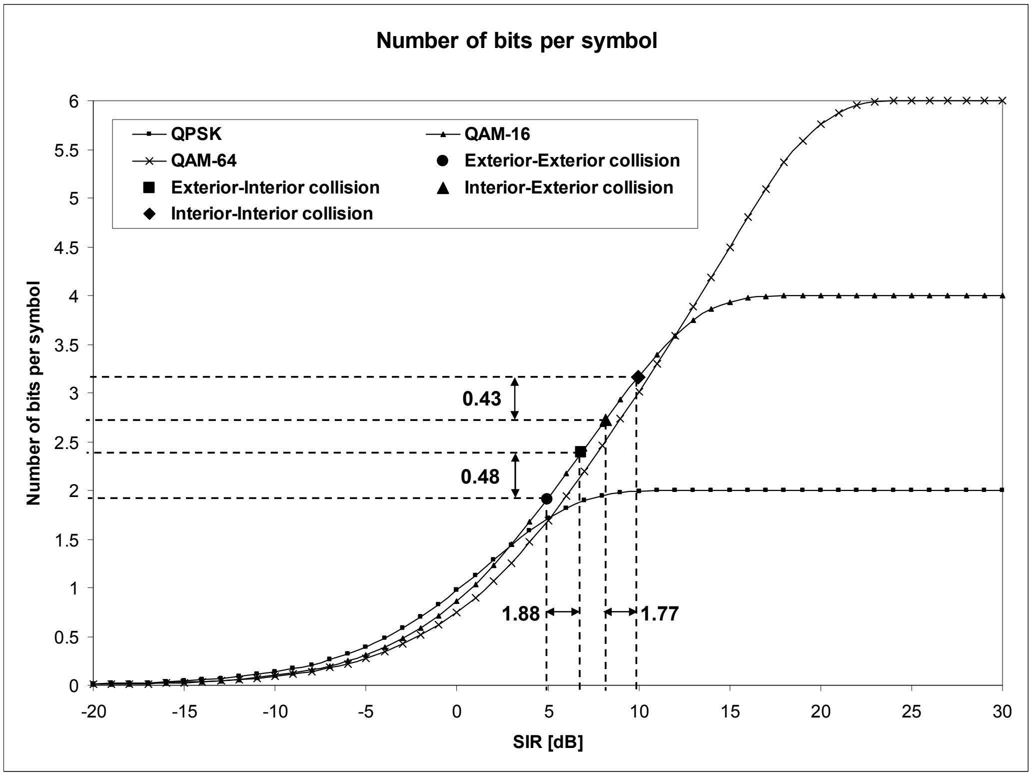


Figure 37: Values of *SIR* in case of different *PRB* collisions

As it is expected the exterior-exterior collision results in the lowest and the interior-interior collisions results in the highest level of *SIR* per *PRB*. The Figure 37 shows that the achieved gain in terms of information bits when an exterior-exterior collision is replaced by an exterior-interior collision is lost due to the reduction in the information bits when an interior-interior collision is replaced by an interior-exterior collision. As we can see that the achieved gain in terms of the bits per symbol values (0.48 bits per symbol on average) almost equals to the introduced loss (0.43 bits per symbol on average). Therefore, the *ICIC* algorithm is not able to give improvement at high traffic load. This phenomenon occurs in low loaded system as well, but in that case there are unused *PRBs*, which means that not all avoided exterior-exterior collisions introduce the above mentioned loss factor in the given *TTI*. In the real system the fully loaded cells are not so common, hence the *ICIC* algorithm is still worth to be used.

In case of *ICIC Start Index Geometry Weight* and *ICIC Random Index Geometry Weight* the collision concept is not defined, because there is no exterior and interior differentiation in the algorithms. However, the reason for the disappearing improvement in system capacity is the same as the one in the exterior/interior classification cases, only the collisions are interpreted in a more generalized sense.

To summarize the presented simulation results, we can say that the highest improvement can be achieved with narrowband users at low and moderate traffic load. As the traffic load in the system increases or the users become more wideband, the gain of the *ICIC* algorithm decreases, finally the difference in throughput between the reference and the ICIC algorithm disappears.

Finally, we can draw two conclusions observing the simulation results regarding to the *ICIC* algorithm variants. The first one is that the *ICIC* algorithm is worthwhile to be applied especially at low and moderate traffic load. The second conclusion is that the randomized schemes do not give significantly lower throughput values, which means that the *ICIC* algorithm can be employed without using frequency plan.

7. Summary

In the thesis an overview of the most important channel allocation schemes used in circuit switched systems have been presented. The channel allocation technique is responsible for assigning radio channels to mobile users. In the Long Term Evolution (*LTE*) system the radio resource assignment technique is different compared to ones used in circuit switched systems. A suitable channel assignment scheme can increase the system capacity by reducing the level of interference in such a way so that it takes the resource assignment of other cells into account and coordinates the resource allocation to avoid the cases when two interfering users in adjacent cells use the same resource blocks. Such channel assignment techniques are also referred to as Inter-Cell Interference Coordination (*ICIC*) in this context.

In the thesis a set of *ICIC* algorithms has been designed, implemented and evaluated. All of the proposed algorithm variants have been integrated into the scheduling concept used in *LTE*. The objective of the algorithms is to avoid the cases when two users close to each other in adjacent cells use the same resource block. None of the suggested algorithms requires communication between base stations. Two variants (*ICIC Start-Stop Index*, and *ICIC Start Index*) differentiate two group of mobile users, interior and exterior users. They try to assign radio blocks to users such that the exterior users use different resource blocks in adjacent cells (3-reuse for exterior and 1-reuse for interior users). The *ICIC Start Index Geometry Weight* scheme uses a generalized classification of users determined by a certain geometry weight for each user, and it tries to avoid the cases when two “most exterior” users use the same resource block in neighbor cells. The *ICIC Random Start Index* is the randomized variant of the *ICIC Start Index* scheme, which means that it does not require frequency plan to coordinate the assignment of resource blocks to users. The fifth variant of the *ICIC* algorithm (*ICIC Random Start Geometry Weight*) is the combination of *ICIC Start Index* and *ICIC Start Index Geometry Weight* schemes, which also avoids the need for frequency planning.

To evaluate the proposed set of algorithms a radio network simulator developed by Ericsson has been extended. The simulation results showed that the

ICIC algorithms achieve significant improvement in user bit rates as well as in system capacity at low and moderate cell load. The comparison of the five algorithm variants showed that the avoidance of frequency planning does not result in significant loss in the achieved improvement in capacity. However using the geometry weight based classification of users instead of exterior/interior classification provides significant additional gains. Therefore, the overall conclusion is that the algorithms operating without a frequency plan and using geometry weight classification of users are the best compromises from the complexity and performance point of view.

Abbreviation list

3GPP	3rd Generation Partnership Project
3G	3rd Generation
CQI	Channel Quality Indicator
DL	Downlink
FFT	Fast Fourier Transform
HARQ	Hybrid Automatic Repeat Request
ICIC	Inter-Cell Interference Coordination
IP	Internet Protocol
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
NP	Non-deterministic Polynomial time
OFDM	Orthogonal Frequency Division Multiplexing
O&M	Operation and Maintenance
PAPR	Peak-to-Average Power Ratio
PG	Path Gain
PL	Physical Layer
PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RLC	Radio Link Control
RoHC	Robust Header Compression
RRM	Radio Resource Management
SC-FDMA	Single Carrier Frequency Division Multiple Access
SIR	Signal-to-Interference Ratio
SINR	Signal-to-Interference-and-Noise Ratio
TCP	Transmission Control Protocol
TTI	Transmission Time Interval
UE	User Equipment

UL	Uplink
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access

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