Technical University of Denmark

Advanced Delivery System for 5G-enabled Photonic Networks

Alberto Gómez Gonzalvo

Bachelor Thesis

S136067

May 2014

DTU Fotonik, Technical University of Denmark, Kgs. Lyngby, Denmark

Supervised by:

J.J. Vegas Olmos

DTU Fotonik
Department of Photonics Engineering

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This report is a part of the requirements to achieve the Bachelor of Science (BSc) in Telecommunications at Technical University of Denmark.

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Abstract

The advent of mobile devices such as smartphones or tablets demanding high capacity services drives a solution for next generation wireless networks. Wireless and optical networks are converging to increase the bandwidth available for the end users.

The deployment of Radio-over-Fiber technologies, which allow the distribution of millimeter-wave signals on the optical domain, is a very promising solution for the migration towards higher frequency bands. This would allow fulfilling capacity requirements of next-generation access networks.

Passive distribution of Radio-over-Fiber channels is now well understood; however, it does not rip all the benefits optical networks can provide. Active distribution, where signals are routed on-the-fly by the network, is currently under heavy research.

This bachelor thesis presents a possible solution to provide the next generation base stations with high-speed communications. This thesis has focused on the distribution of optical channels in a Radio-over-Fiber system. Dynamic and Hybrid Channel Allocation techniques are presented as a way to increase the capacity in optical-wireless systems.

In this thesis, we have developed a novel algorithm for the distribution of optical channels based on the blocking probability reduction. We present it as a technique to increase the performance of the network.

Furthermore, we report on an experimental characterization of an optical switch, which is the main building block to construct networks supporting Hybrid Channel Allocation methods.

Acknowledgements

First of all I would like to thank J.J. Vegas Olmos for guiding me not only through this thesis but also through any issue concerning Danish life.

Thanks also to Professor Idelfonso Tafur Monroy for challenging me with the channel allocation topic as well as for embedding me at the Metro-Access and Short Range Communications Group.

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From UPC Barcelona, I would like to acknowledge Joan M. Gené Bernaus for encouraging me to come to DTU Fotonik. Thanks also to Esteve Pallarès Segarra who always found a moment to answer my questions related with Queuing Theory. I would not like to forget my classmates, especially to *Els Competitius* for these great four years becoming engineers.

And finally, I would like to thank my parents, brother, family and friends for the trust they have always bestowed on me.

Summary of Original Work

The following original publication has been reached as result of the research within this Bachelor's Thesis:

PAPER 1: A. Gomez Gonzalvo, J.J. Vegas Olmos, and I. Tafur Monroy, "Performance of an algorithm for hybrid channel allocation in an optical radio-over-fiber network," *In preparation for* Asia Communications and Photonics Conference 2014.

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Acronyms

AWG	Arrayed Waveguide Grating
BS	Base Station
CAGR	Compound Annual Growth Rate
CO	Central Office
DAS	Distributed Anenna System
DBA	Dynamic Bandwidth Allocation
DCA	Dynamic Channel Allocation
DML	Directly Modulated Laser
DML	Directly Modulated Laser
DSB	Double Sideband
DSL	Digital Subscriber Line
ED	Envelope Detector
FCA	Fixed Channel Allocation
HCA	Hybrid Channel Allocation
IF	Intermediate Frequency
ISO	International Organization for Standardization
LO	Local Oscillator
MEMS	Micro Electro-Mechanical System
OSI	Open Systems Interconnection
Qos	Quality of Service
RF	Radio Frequency
RN	Remote Node
RoF	Radio over Fiber
SSB	Single Sideband
TDM	Time Division Multiplexing
WDM	Wavelength Division Multiplexing

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1

Introduction

The emergence of new applications requiring high-capacity services such as HD video streaming, cloud storage or online gaming is driving the need for high-performance of wireless networks.

Besides the growth of number of users experienced so far, studies forecast that for the upcoming years the data traffic will continue growing very fast. One of the areas where the traffic is growing faster is the mobile one – it is forecasted that by the end of 2014 the number of mobile-connected devices will exceed the world's population [1].

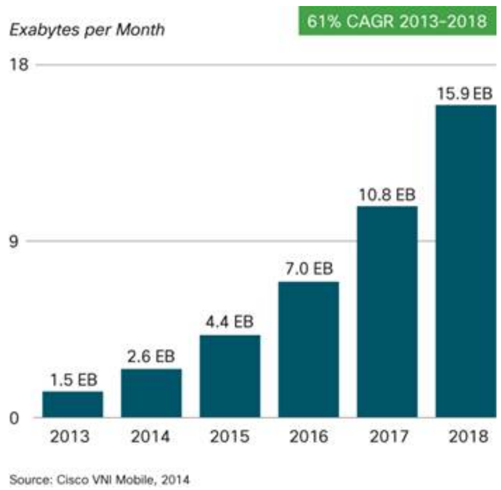

Figure 1.1 Cisco Global Mobile Data Traffic Forecast Update, 2013–2018

As depicted in Figure 1.1, mobile data traffic is expected to undergo an almost 11-fold increase by 2018, experiencing a Compound Annual Growth Rate (CAGR) of 61% between 2013 and 2018.

All the users should be able in a near future to connect to the same services regardless of whether they are using a wired or wireless connection. Therefore, we need to provide a wireless end-user network capable of giving high-capacity services.

1.1 Problem statement

Copper lines are no longer a solution for future access networks [2]. Digital Subscriber Line (DSL) services became a big success for telecom companies, since they were able to provide broadband to many people in a very cheap way.

However, in copper links, signals suffer a very strong attenuation when transmitting over long distances. Thus, optical links are meant to be the links for future networks. As shown in Figure 1.2 none of the DSL techniques are able to provide more than 100 Mbit/s, even if we take really short transmission distances. Therefore, moving to optical networks is mandatory.

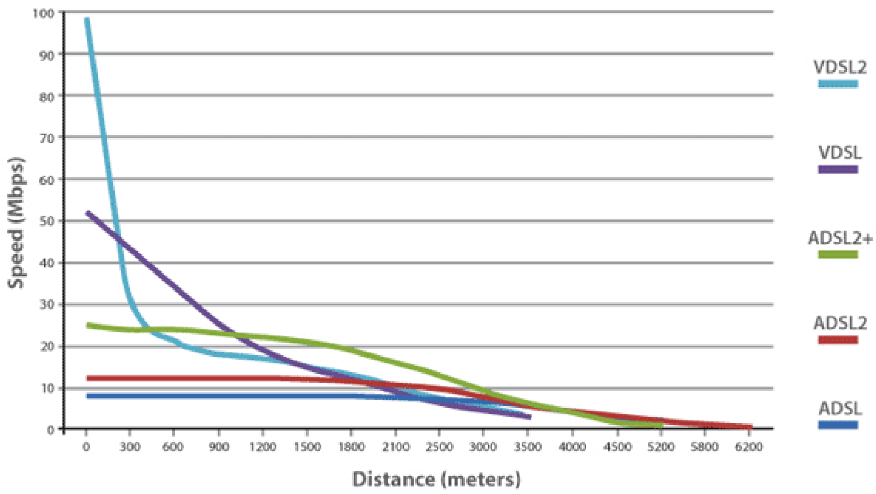

Figure 1.2: Different bit rates over distance for different DSL techniques. Source: OFCOM

We have also a lack of available bandwidth in the wireless medium. The current spectrum is very crowded and therefore a migration to another frequency band is needed.

Moreover, we have to cope with the mobility of the users in an efficient and simple way. We will need to be able to provide high data rate to all the users even if there are many users located in the same cell. We will introduce the Photonic - Dynamic Channel Allocation technique as a solution for this problem.

In this thesis we will assess a novel algorithm for dynamically allocate the wireless channels in a millimeter-wave Radio-over-Fiber access network.

1.2 State-of-the art

Different solutions for access networks have been released commercially. One of the novel research lines for optical access networks is the Radio-over-Fiber (RoF) solution, which will be explained in Section 2.2. Different RoF techniques have been widely studied and reported, as in [3].

For designing the next generation access networks we will not only need a good solution of a particular Engineering field, but we will need the convergence of different research lines, combining for example photonic, wireless and advanced data coding techniques. This is related to the work done in [4]. With our work we have merged the fields of optical communications, wireless technologies and queuing theory.

Related to dynamic optical access networks, work has been done so far demonstrating experimental dynamic reconfigurable networks on the optical domain [5] [6].

In the Teletraffic area, many algorithms for an effective distribution of bandwidth have been reported. For example, parameters such as the velocity of the mobile users are taken into account to allocate the bandwidth [7]. Another possibility is to try to reduce the handoff occurrence [8]. Our algorithm is based on the reduction of the blocking probability, as done in [9].

1.3 Methodology

The methodology in this project comprises literature research, theoretical and experimental work and coding. First, I conducted a literature research survey in Radio-over-Fiber technique as well as optical switching technologies.

Research in Teletraffic theory was also done, trying to merge this field with photonic and wireless networks.

The implementation of the algorithm and the simulation of a network were done in MATLAB. The subsequent analysis and quantification of the performance of the algorithm was also done in MATLAB.

The experimental work included a physical characterization of an optical switch in the laboratory, in order to see whether it fulfilled the specifications provided by the manufacturer. It also gave us the necessary training for future experimental demonstrations of this thesis.

1.4 Contributions

This project has been conceived within a broader project the purpose of which is to test an access network based on mm-wave Radio-over-Fiber with dynamic channel allocation capability. The first stage of the project included the design of the system architecture based on the work done so far and reported in the state-of-the-art. Marti Sales designed an electronic control board for a commercial optical switch [10].

Our work included the test of the optical switch with the electrical control board, a very important step for a future physical implementation. Moreover, we developed an algorithm for a Hybrid Channel Allocation-based network targetting the reduction of the blocking probability for the connected devices.

The future work for this project will include the experimental testing of the switch working with mm-wave signal, Radio-over-Fiber technique and dynamically allocating the channels with our algorithm.

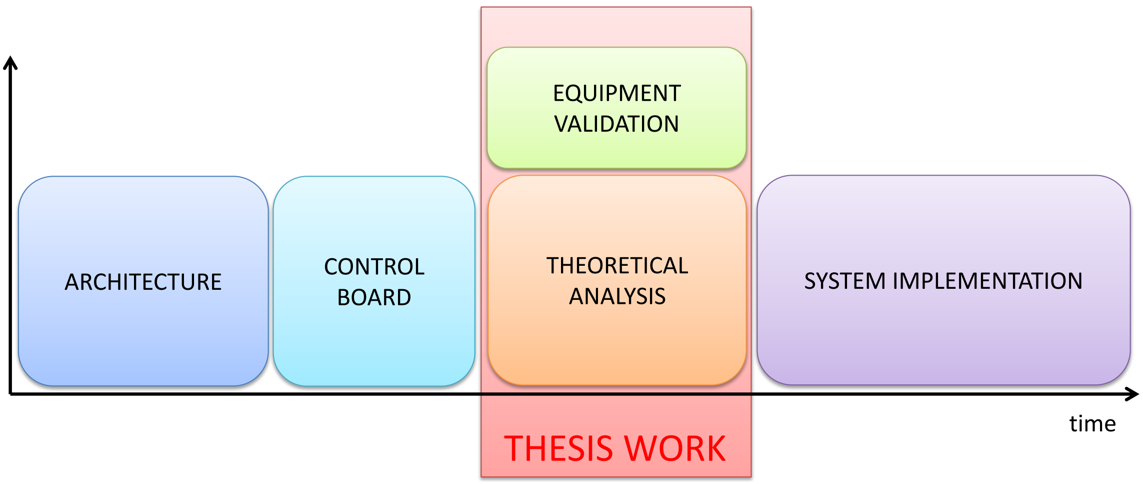

Figure 1.3. Project background and follow-up

We are currently working on a paper related with the research done within this thesis that will be submitted to *Asia Communications and Photonics Conference 2014*.

1.5 Thesis Outline

The remainder of the report is organized as follows:

Chapter 2 introduces a theoretical background about hybrid optical wireless systems.

Chapter 3 presents the different channel allocation techniques. It also states the differences between them and their advantages and drawbacks.

Chapter 4 presents the developed algorithm for allocating channels in a HCA-based network.

Chapter 5 assesses the performance of the algorithm by testing it in different networks. We also quantify its performance statistically.

In Chapter 6 the experimental setup and results are presented.

Finally, in Chapter 7, the conclusions of the thesis are summarized and the future work is presented.

2
Hybrid optical-wireless links

This chapter presents a possible solution for high-capacity next generation optical access networks. The Radio-over-Fiber technique is introduced as a technology for the distribution of Radio Frequency signals on the optical domain.

2.1 Migration to mm-wave range

The capacity of hybrid optical-wireless networks is limited by the wireless bandwidth bottleneck [11]. The lack of bandwidth makes that new spectral bands must be exploited. As depicted in Figure 2.1, current wireless networks such as UMTS or LTE are in a very crowded spectrum, so the data rate achievable by the users is constrained by the low bandwidth available.

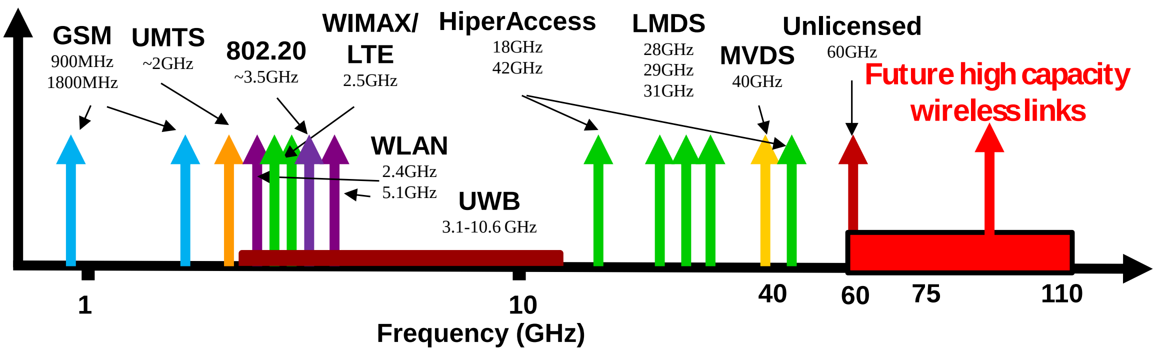

Figure 2.1. Wireless frequency spectrum [3]

Therefore, we will move from the microwave range to the millimiter-wave (mm-wave) band. The mm-wave region corresponds to radio frequencies from 30 GHz to 300 GHz [12].

2.1.1 Problems at mm-wave range

Let the free-space path loss formula (2.1) be

$$P_R = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \quad (2.1)$$

where P_R is the received power, P_T is the transmitted power, G_T is the gain of the transmitter antenna and G_R of the receiver one, d is the distance between antennas and λ is the wavelength of the transmitted wireless frequency.

We can observe that the lower the wavelength, the lower the received power is. Thus, by increasing the frequency, the fading that the wave suffers also increases; since $f = \frac{c}{\lambda}$, where c is the speed of light.

Therefore, in a mm-wave wireless link, more base stations (BSs) are required– comparing e.g. to a 4G environment–, as the cell coverage area of a mm-wave BS is lower. Working in a mm-wave frequency band the coverage area of each access point will be reduced until few tens or hundreds of meters [3]. Since the number of BSs will increase, a base station as simple as possible is required.

In this scenario, the central office should contain all the complex functionalities of the system, simplifying the design of the BSs. A possible solution to simplify the BS design is to apply Radio-over-Fiber technologies.

2.2 Radio-over-Fiber

2.2.1 Motivation

The Radio-over-Fiber technology deals with the integration of wireless and optical networks. It enables a flexible access network capable of offering wireless broadband connectivity. A deep analysis of the theoretical background is beyond the scope of this document, but the key points of the RoF technique are presented.

The RoF architecture of the network may vary with the targeted application. However, the most basic RoF system consists of a Central Office (CO) and a base station, connected with an optical link that conveys the information in Radio Frequency (RF) (Figure 2.3).

The goal of a wireless system is to transmit the data in Radio Frequency through the wireless channel, where a receiver decodes the information with an antenna. Wireless signals must be transmitted in RF, so the data has to be up-converted somewhere in the link. To up-convert the data we have two possibilities, depicted in Figure 2.2 and Figure 2.3. The first one – Baseband over Fiber – consists of the transmission of the signal from the CO to the BS in baseband, so the up-conversion is done at the BS. The other one – Radio over Fiber – conveys the signal modulated in RF directly from the CO.

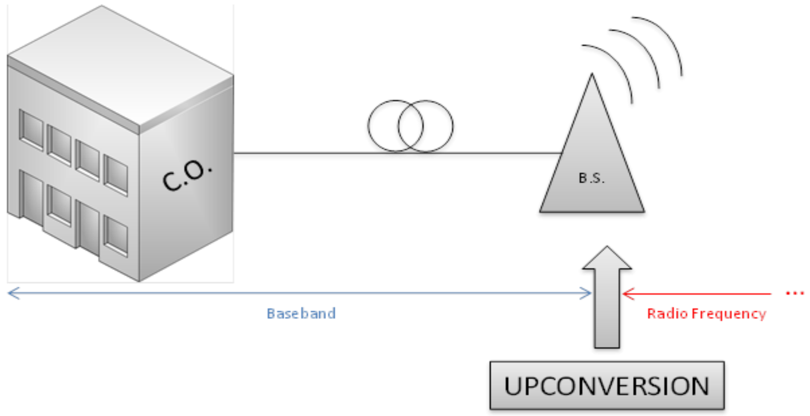

Figure 2.2: Baseband over fiber transmission

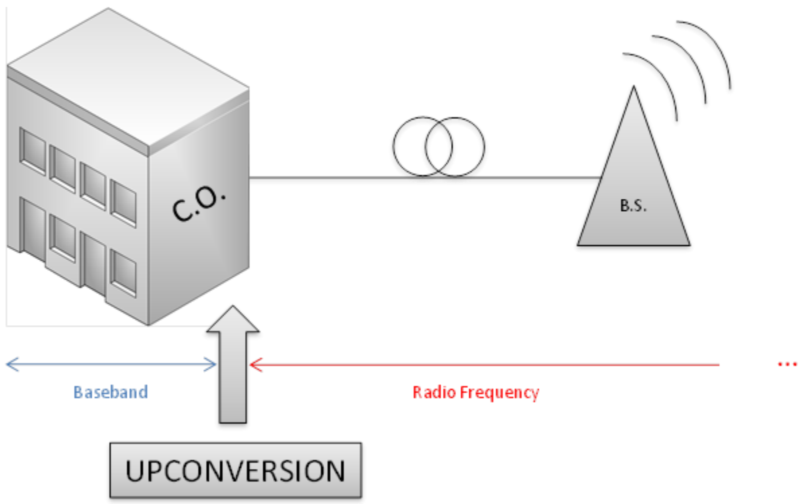

Figure 2.3: Radio-over-fiber transmission

In Baseband over Fiber technique, the BS does the up-conversion. This means that a mixer must be placed in each of the BSs, increasing the complexity of the total system with large number of base stations.

On the other hand, by up-converting the signal into RF at the central station, the BS complexity is not a problem. For example, in the simplest configuration, the BS is a photodiode to convert from the optical domain to the electrical domain, connected to an antenna to transmit the data in RF. Therefore, in a mm-wave hybrid optical fiber-wireless system, RoF techniques will be adopted.

2.2.2 Modulation of the lightwave

In a RoF environment, the CO must be able to up-convert the data into Radio Frequency and send it through the fiber to the different base stations.

We have two different possibilities for modulating the information into RF. The first one is the called Double Sideband (DSB) modulation. A DSB system modulates the same data in both lobes of the RF signal. One possibility for modulating the data with DSB technique is depicted in Figure 2.4.

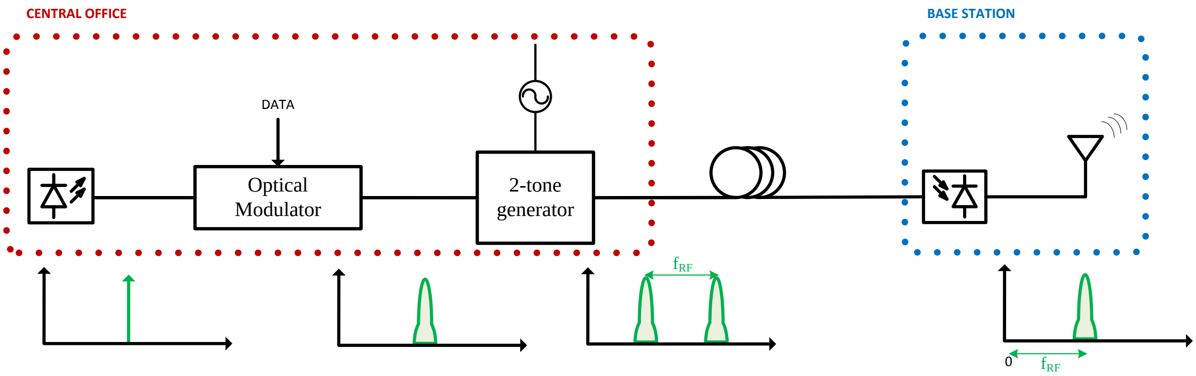

Figure 2.4. Transmission of RF wireless data with optical DSB generation

The main disadvantage of this technique is the chromatic dispersion sensitivity. Depending on the fiber length, the modification of the total chromatic dispersion can make one lobe to be the same as the other lobe but with opposite sign. Then, the combination of the two lobes at the receiver side would destroy the signal. Algorithms have been proposed to compensate this problem [13].

On the other hand, a Single Sideband (SSB) system modulates the data only at one lobe of the signal, keeping at the other one only the carrier.

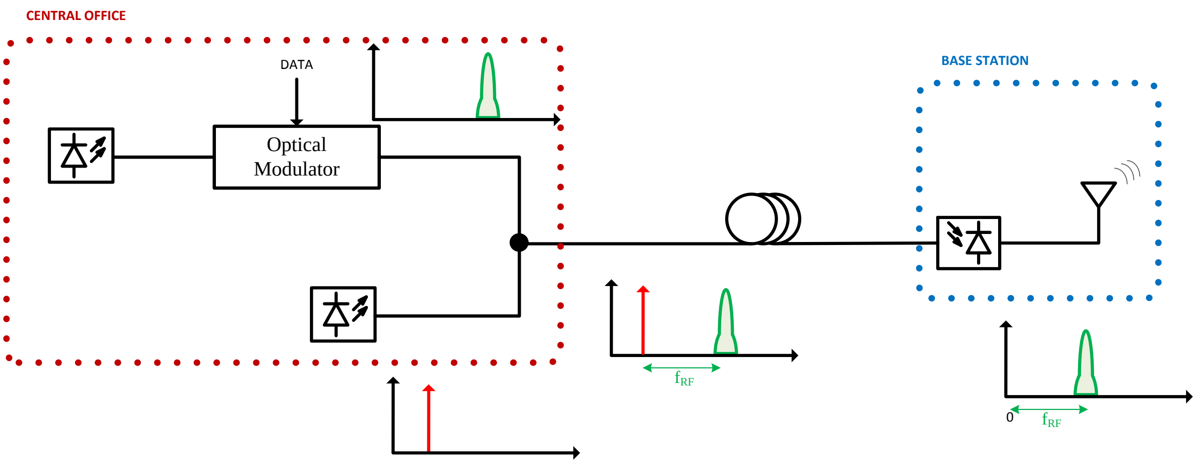

Figure 2.5. Transmission of RF wireless data with optical SSB generation

The main advantage of the SSB approach is that we do not have the dispersion problem present in a DSB modulation. However, with SSB technique we are only able to transmit the half amount of power that we can send with DSB, since we only transmit in one of the two lobes of the RF signal.

With both approaches (DSB and SSB) we are fulfilling the RoF requirement of conveying the data in RF through the fiber, so the design of the BS is simplified.

2.2.3 Detection of the signal

For the reception of the mm-wave signals radiated from the BS antennas we have two main technologies, direct and coherent detection.

The first one is based on the direct detection principle. It is an extremely simple down-conversion of the signal, performed using only an envelope detector (ED), usually a Scottky diode. We are only able to decode amplitude-based modulation formats, since only the amplitude of the envelope is detected, not the phase. Therefore, modulation formats such as PSK or QAM are not supported.

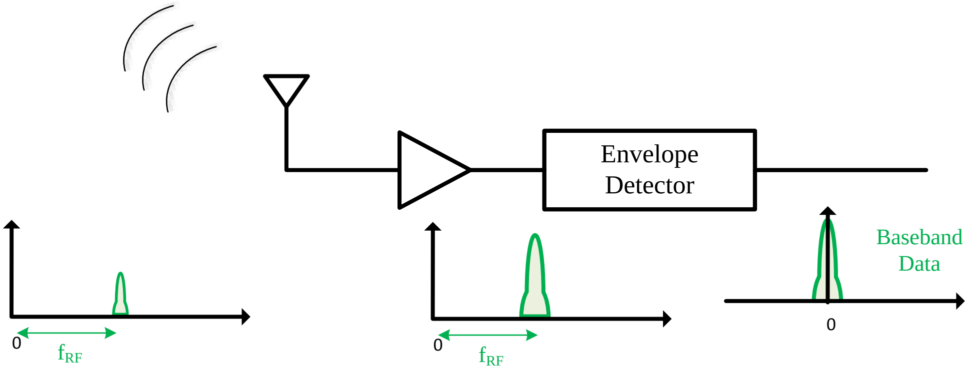

Figure 2.6. Down-conversion of the wireless signal using ED

The other possibility for detecting the signal is to do a coherent down-conversion. It is based on electrical mixing of the signal with a local oscillator placed after the receiver antenna. Usually the operational bandwidth of this type of systems is higher than the direct-detection ones [3], since they do not have the bandwidth limitation of a Schottky diode. Moreover, coherent down-conversion systems can recover the phase and the amplitude simultaneously, allowing the reception of advanced modulation formats.

The down-conversion can be done either to baseband or to an Intermediate Frequency (IF), depending on the frequency of the Local Oscillator (LO).

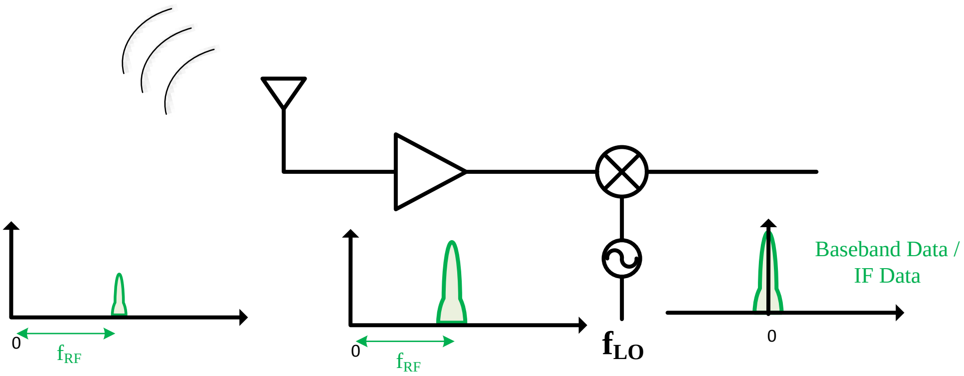

Figure 2.7. Down-conversion of the wireless signal using a mixer and a LO

2.3 Summary

The solution proposed based on mm-wave RoF links is able to provide high-capacity for next generation wireless access networks. However, it also causes some problems, stated in the table below. Thus, to sum up:

ADVANTAGES	DRAWBACKS
High-capacity achievability due to the large bandwidth available in: • Wireless links in mm-wave range • Optical fiber links	Deployment of BSs with very small cell-coverage area
Cost-effective solution based on the simplicity of the BSs	Dispersion problem or half-power problem depending on whether we are using DSB or SSB modulations

Table 2.1. Advantages and disadvantages of mm-wave RoF links

3
Channel Allocation Techniques

This section presents different techniques for channel allocation. The channel allocation in wireless medium is a very important step in the network planning and was widely studied in the late 20th century [14],[15]. The work done in the 80s and 90s focused mainly on the reassignment of channels taking into account aspects such as co-channel interference or frequency reuse.

In a RoF system, the Photonic Channel Allocation defines the way the channels are sent from the central office to the different access points.

There are three types of channel allocation: Fixed Channel Allocation (FCA), Dynamic Channel Allocation (DCA) and Hybrid Channel Allocation (HCA).

3.1 Fixed Channel Allocation

The most used frequency allocation scheme is the Fixed Channel Allocation. FCA technique distributes the channels in a fixed way according to an already defined channel frequency planning. FCA systems have been broadly implemented throughout the years and are systems highly reliable with an optimum frequency preplanning.

With a FCA system, the distribution of the channels is the same all the time and there is no possibility to change it. Therefore, since wireless links present variable traffic profiles, a technique to cope with the mobility of the users is needed.

We have mainly two possibilities for real-time frequency allocation. The first one is the dynamic-bandwidth-allocation (DBA). DBA techniques work with already deployed networks. The other one is to plan a network by applying DCA or HCA.

DBA consists of the application of mathematical algorithms in order to balance the traffic in the network depending on requirements such as the Quality of Service (QoS). These algorithms are mainly implemented in the highest layers of the OSI model (network layer), so their analysis is out of our scope.

Since DBA work with already existing networks, their combination with FCA improves the performance of a FCA scheme and allows the system to be able to cope with the traffic requirements on-the-fly.

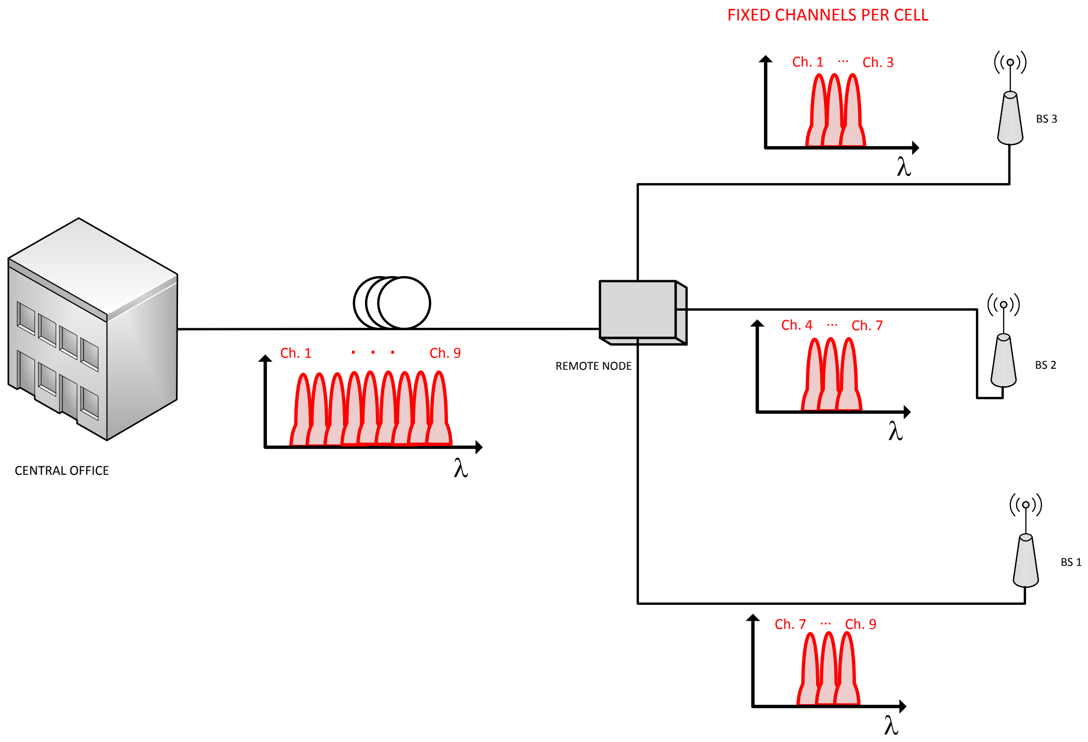

Figure 3.1: FCA-based network

3.2 Dynamic Channel Allocation

DCA technique seems to be a very promising solution for upcoming generations of hybrid optical-wireless access networks. DCA-based networks have the capability to change the allocation of the channels depending on the status of the network. However, they need more computational capacity than FCA networks, since the optimal distribution of channels has to be calculated and implemented.

There are different types of DCA. Wireless-DCA is related to the ability of a wireless network to assign frequency channels from a BS to the final user [5]. We will focus on the distribution of the frequency channels from the CO to all the BSs. In optical wireless systems, this is the technique known as Photonic-DCA.

The allocation of channels is done by the Remote Node (RN) based on wavelength routing, as explained in Section 3.4.

3.3 Hybrid Channel Allocation

Hybrid Channel Allocation is the combination of FCA and DCA. In a HCA scheme we divide into two different sets of channels: the first one is considered for a fixed frequency allocation, using FCA, whereas the other set of channels is a pool to be shared by all the BSs. The second group of channels will be distributed among the different BSs according to the requirements of the network at a certain time.

This technique mixes the advantages of both FCA and DCA techniques [16], such as the stability and reliability of FCA systems and the dropped connections reduction of DCA schemes.

HCA-based networks need less computational complexity than DCA ones, but still more than FCA. On the other hand, HCA offers more flexibility to the network than FCA and less than DCA. Therefore, HCA networks can provide a good tradeoff between the complexity and the flexibility of a network.

The relation between fixed and dynamic channels is a very important parameter in HCA networks as it will define the performance of the network in terms of complexity, flexibility, etc.

The notation used hereafter is the same as the one done in [9], $FixedChannels_{per\ cell}$: $DynamicChannels_{per\ cell}$. It means that if we have 3 cells with 10 fixed channels per cell and 15 dynamic channels in total we will write it as HCA 10:5.

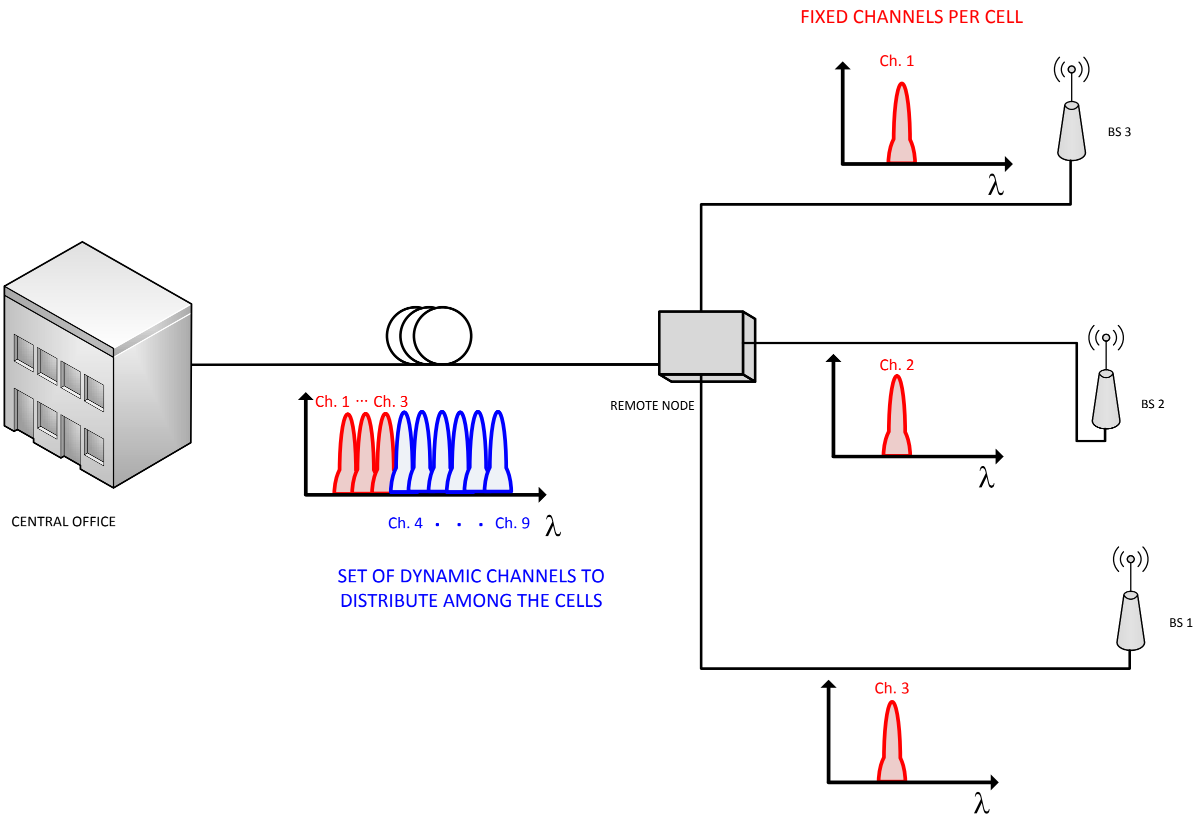

Figure 3.2. HCA-based network.

3.4 Physical implementation

To implement a Photonic - Hybrid or Dynamic Channel Allocation, we need a remote capable of switching optical channels. The switch must work on the optical domain, since a conversion to electrical would drastically reduce the available bandwidth.

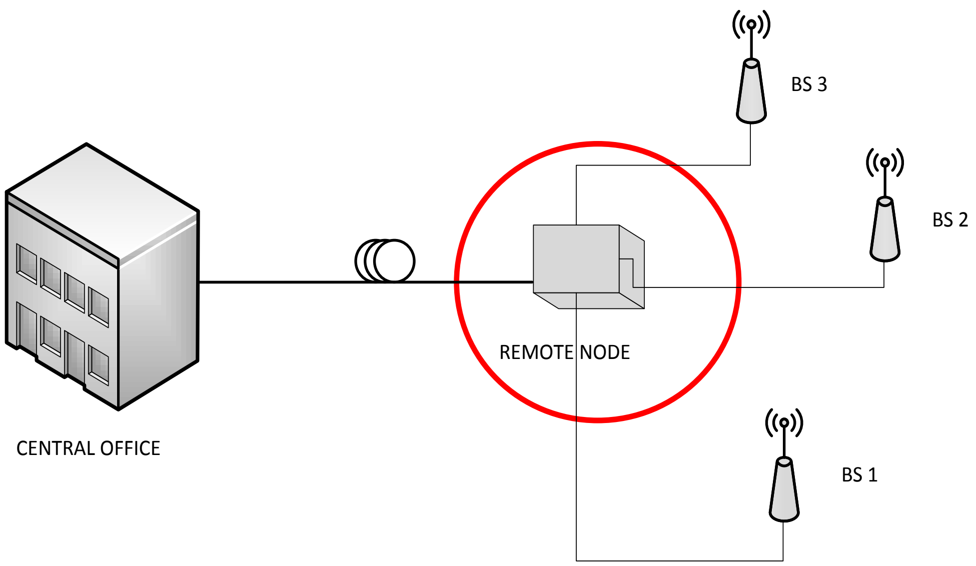

Figure 3.3. Architecture of an access network with a remote node.

The RN must have the ability to perform wavelength routing, i.e. to send optical channels to the different BSs depending on the demands of the network. Nevertheless, the decision for the allocation of the channels can be computed by software on the electrical domain. An algorithm for Photonic-HCA is presented in Section 4.3.

There are different switching technologies which enable dynamic wavelength allocation. The most common technologies for optical switches are optical Micro Electro-Mechanical System (MEMS)-based, thermal, electro optical or acousto-optic. The technology of choice may vary depending on the targeted application, since they have different performance in terms of insertion losses, switching speed, crosstalk, polarization-dependent loss, wavelentgth dependency, scalability, etc. [17].

3.5 Hybrid WDM-TDM System

In order to be able to transmit different channels through the fiber and route them with the remote node, the CO must do a wavelength-based multiplexing. Later on, the channels must be located to different access points with a wavelength-routing system performed by the RN.

WDM technology is a transmission technique for optical signals very similar to an electromagnetic Frequency Division Multiplexing. WDM combines multiple optical signals into a single fiber by transmitting each signal on a different wavelength. Each wavelength defines a channel.

The system also must be able to locate more than one user per channel. Once we have the wireless channels defined, this can be achieved by a Time Division Multiplexing (TDM) of each channel. TDM is a method for transmitting information where a single channel is shared by several users. Each user appears in the channel only a fraction of time, with an alternating pattern.

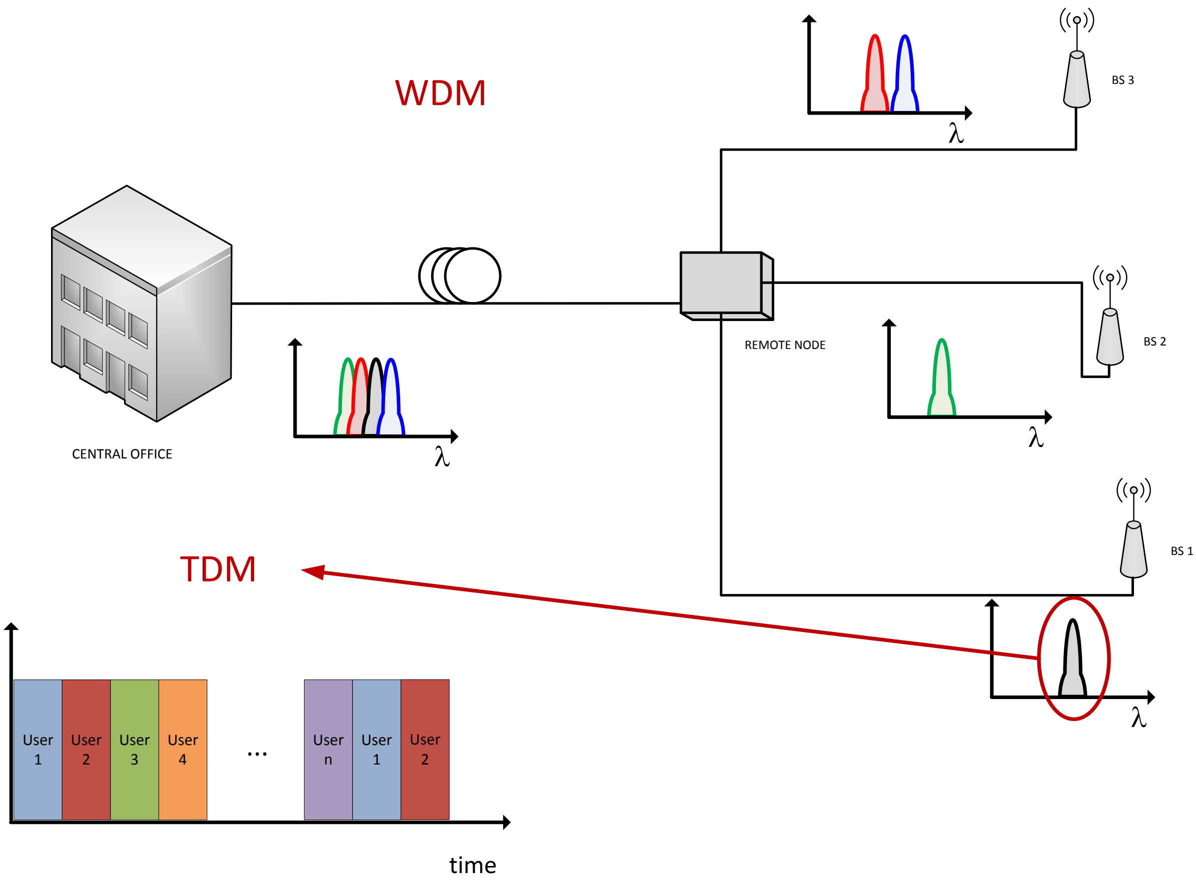

Figure 3.4: WDM/TDM system

4

Algorithm for Hybrid Channel Allocation based on the blocking probability reduction

In this section we present a novel algorithm for a HCA-based network targetting a blocking probability reduction. This algorithm is a proposal to dynamically route the optical channels. We do not take into account very important aspects in the network planning as the cross-interference between cells or the frequency reassignment.

Therefore, this algorithm must have future upgrades bearing in mind these constraints.

4.1 Bandwidth utilization

In FCA networks, the lack of frequency channels due to the overflow of the system at certain periods of time is an existing problem. In this section we relate analytically this problem with the percentage of used bandwidth, call arrival rate and the average duration of a call.

We consider a system where the maximum number of users in each cell is N_{max} , taking into account all the channels. The call arrival rate is λ, and the average duration of each call is T. We can compute the number of arrivals $N_{arrivals}$ during a time interval T as

$$N_{arrivals} = \lambda \cdot T \tag{4.1}$$

Assuming that the system has a loss probability of p_{loss} , the processed arrival rate, defined as the arrival rate successfully delivered to the users, can be computed as

$$\lambda_p = \lambda \cdot (1 - p_{loss}) \tag{4.2}$$

By applying now Little's law, the number of users that will be in the system is

$$N_{system} = (1 - p_{loss}) \cdot \lambda \cdot T \tag{4.3}$$

If we divide both sides of the equation by the maximum number of users, the quotient $\frac{N_{system}}{N_{max}}$ will give us the ratio of used bandwidth. Thus,

$$Util_{BW} = \frac{(1 - p_{loss}) \cdot \lambda \cdot T}{N_{max}} \quad (4.4)$$

We have related the percentage of used bandwidth with the call arrival rate and the average duration of a call.

Figure 4.1 shows the analysis of the used bandwidth by varying the arrival rate (in calls/s) and the average duration of a call (in seconds/call).

The utilization has been computed with a maximum number of users $N_{max} = 100$ and a loss probability $p_{loss} = 0.05$.

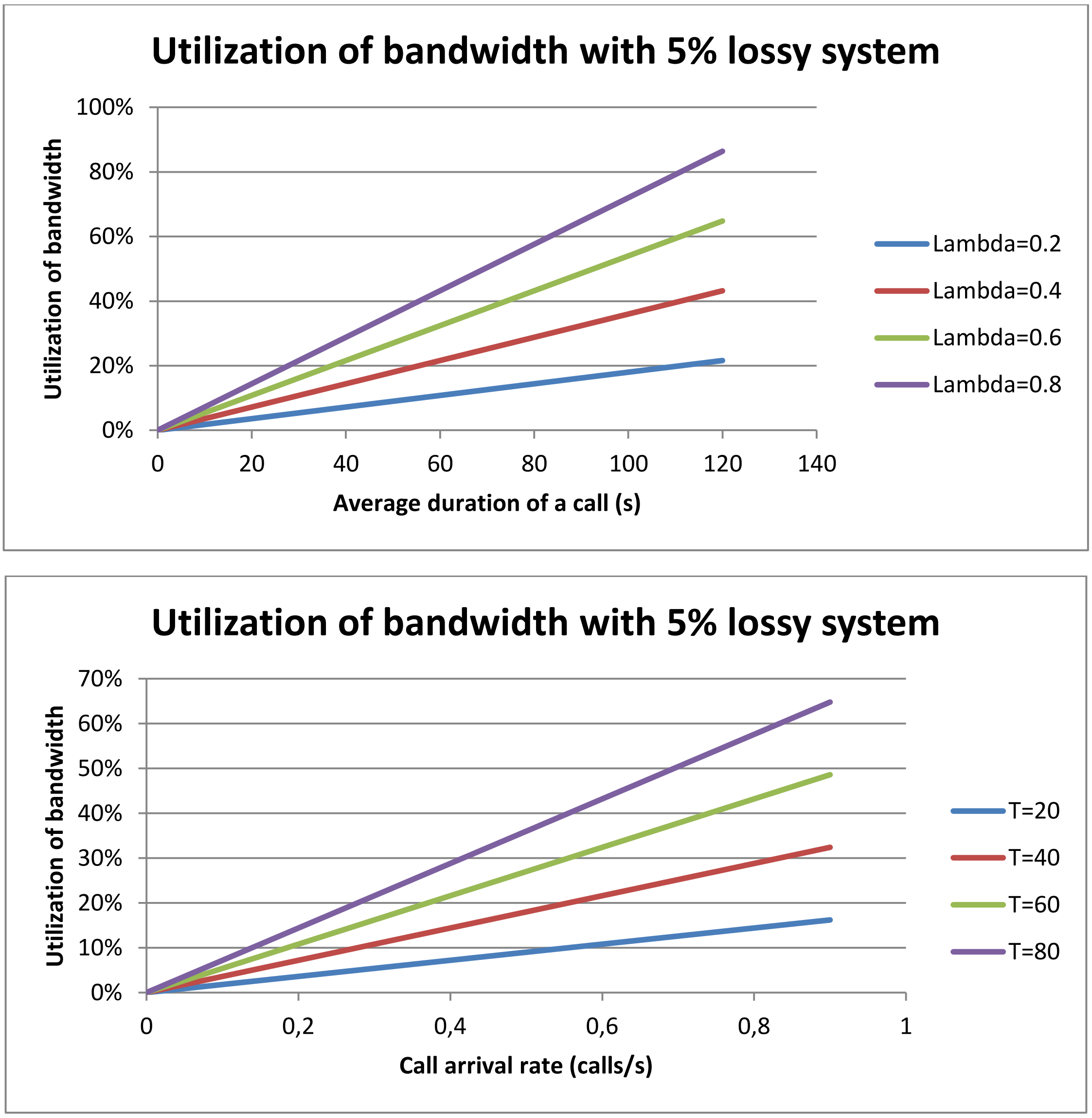

Figure 4.1. Percentage of used bandwidth by varying the duration of a call and the arrival rate

With a dynamic allocation of the channels we can change the percentage of used bandwidth dynamically over the time. So, by increasing the channels in a cell at the expense of reducing in another one, we also increase the maximum number of users that this cell can handle, so we reduce the percentage of used bandwidth in this cell. Therefore, we reduce the loss probability p_{loss}.

4.2 Blocking probability analysis

The Dynamic Channel Allocation procedure has the advantage of reducing the blocking probability of a user [9]. The blocking probability describes the fraction of time that a connection is denied due to insufficient transmission resources in the network.

To fit a wireless system in a Markovian model, we have to make several assumptions [18]:

- Infinite population, who generate a total arrival rate of λ calls/s following a Poisson distribution
- The average duration of a call is T seconds. Thus, the finishing rate of the system is $\mu = \frac{1}{T}$ calls/s
- A single call needs 1 free server for being served
- The cell has N servers:
  - Each cell has $n_{channels}$ channels
  - Each channel handles $n_{usersperchannel}$ servers
  - Each server supports only one user at the same time
  - Thus, each cell handles $N = n_{channels} \cdot n_{usersperchannel}$ users
- The system has not any queue: when we try to make a call and there are no servers available, the call is blocked and the connection is lost without waiting

Taking into account all these considerations, each cell can be modeled as a Markov chain of N states, where the i^{th} state means that there are i occupied servers. With a DCA system, we will be able to change dynamically the N parameter of each cell.

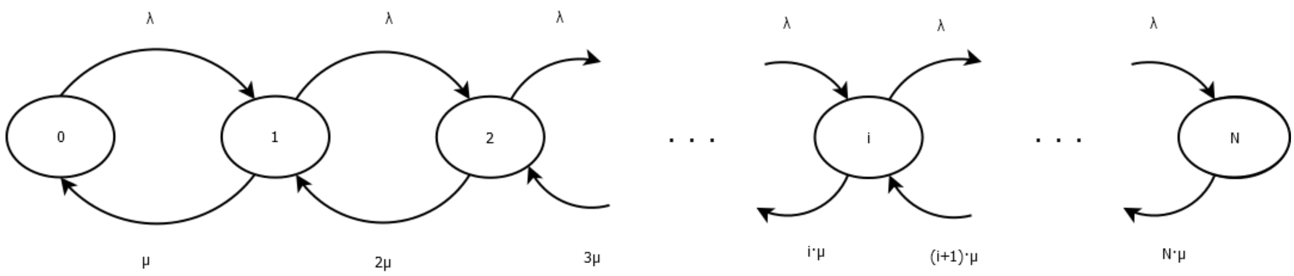

Figure 4.2. Markov chain for systems without queue

In this model, if we are in the i^{th} state, we can go to another state:

- If there is a new arrival, we go to state $i+1$, where we have $i+1$ occupied servers
- If a call ends, we will go to i-1 state, releasing 1 server

Therefore, in the extension of Kendall's notation [19], we can model our system as an M/M/m/m, which in our particular system means

$$Poisson\ arrivals/Exponential\ service\ time/N\ servers/N\ places\ in\ the\ system$$

We can define π_i as the probability of being at the i^{th} state. In statistical equilibrium, the incoming arrival rate to a state must be the same as the outputted finishing rate [18]. Therefore,

$$\begin{cases} \lambda\pi_0 = \mu\pi_1 \\ \lambda\pi_1 = 2\mu\pi_2 \\ \dots \\ \lambda\pi_{N-1} = N\mu\pi_N \end{cases} \tag{4.5}$$

And solving the equation system (4.5) recursively we obtain

$$\pi_i = \frac{1}{i!}\left(\frac{\lambda}{\mu}\right)^i \pi_0 \tag{4.6}$$

We calculate π_0 knowing that the probabilities must satisfy

$$\sum_{k=0}^{N} \pi_k = 1 \tag{4.7}$$

By replacing (4.6) in (4.7)

$$\sum_{k=0}^{N} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k \pi_0 = 1 \rightarrow \pi_0 = \frac{1}{\sum_{k=0}^{N} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k} \tag{4.8}$$

And then we can express the probability of being in the i^{th} state as

$$\pi_i = \frac{\frac{1}{i!}\left(\frac{\lambda}{\mu}\right)^i}{\sum_{k=0}^{N} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k} \tag{4.9}$$

This formula is known as the Erlang-B formula [18].

The probability of having a denied connection due to the lack of available servers is the probability of being at the state N. This is the definition of the blocking probability P_B

$$\pi_N = P_B = \frac{\frac{1}{N!}\left(\frac{\lambda}{\mu}\right)^N}{\sum_{k=0}^{N} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k} \tag{4.10}$$

With a DCA procedure we are able to change this blocking probability dynamically, either by increasing or reducing the number of channels and therefore the servers at each cell N. Thus, by increasing the number of dynamic channels in our cell we reduce the blocking probability.

4.3 Proposed algorithm

As mentioned, one of the targets of both DCA and HCA techniques is to reduce the blocking probability. Hence, the solution we propose is an algorithm to distribute dynamic channels based on the reduction of the blocking probability in all the cells. The flowchart of the proposed algorithm is depicted in Figure 4.3.

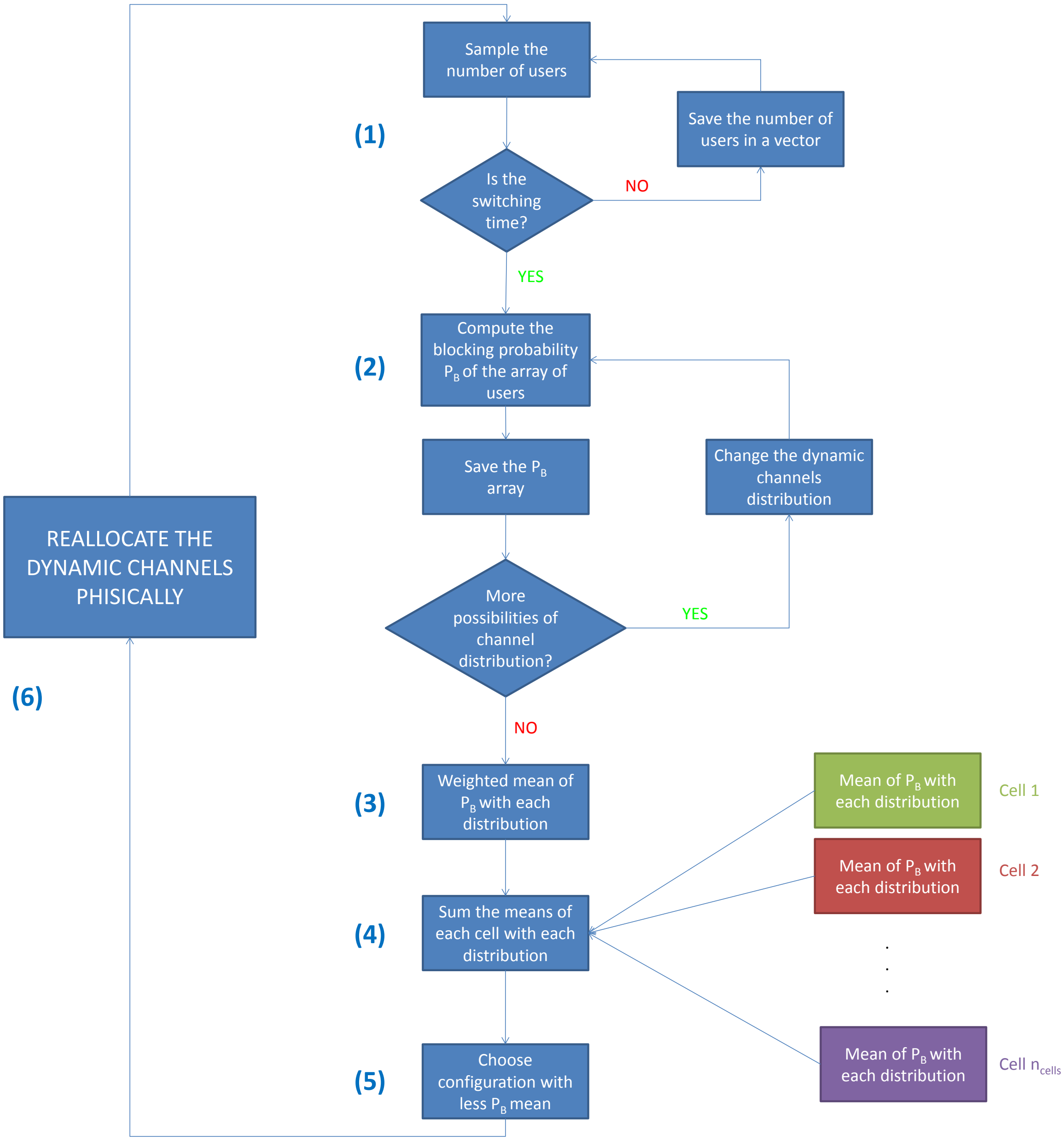

Figure 4.3. Flowchart of the proposed HCA algorithm based on blocking probability reduction

We start the algorithm by saving the number of users within a certain period of time **(1)**, controlled by the variable of the system *switching_time*, which is the time elapsed since the last reallocation of channels. Once we have it, we compute the blocking probability with all the possible distributions of dynamic channels **(2)**. This is, if we had 2 cells and 3 dynamic channels, we would calculate the blocking probability with the 4 different possibilities, as shown in Figure 4.4.

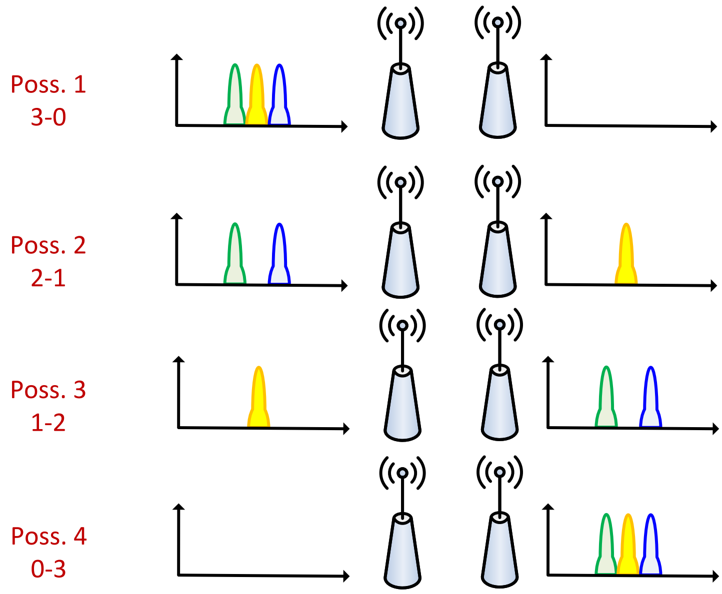

Figure 4.4. Different possibilities for channel distribution

At this point we have the blocking probability measured over the time, with all the possibilities of channel allocation. Since the number of users is varying throughout time, we do a weighted mean of the blocking probability with all the possibilities **(3)**. By doing a weighted mean we take into account the evolution of the users. We put more emphasis to the last users before the switching time and less to the previous ones.

Then, we send this information to the remote node, where we do the summation of the blocking probability with each possible channel distribution **(4)**. This gives us the amount of total blocking probability at the system with each allocation.

The criterion to choose one of all the different configurations is simple: we choose the one with less blocking probability mean **(5)**. When we have chosen the new channel distribution, we reallocate the physical optical channels and we start the algorithm again **(6)**.

Steps **(1)** and **(6)** need an implementation in the physical domain, whereas the other steps are done by software.

The main issue with this algorithm is that we calculate the optimum channel distribution at a certain period of time $[t, t + switching\_time)$, and we use this distribution for allocating the channels at the interval $[t + switching\_time, t + 2 \cdot switching\_time)$, so in the next iteration of the algorithm. However, if we choose a *switching_time* short enough to be able to cope with the mobility of the users, this would not be a problem.

Section 5.5 shows a blocking probability effective reduction of 97% of the times we ran the algorithm.

4.3.1 Modifications of the algorithm

Although the algorithm presents very good performance in terms of blocking probability reduction (Section 5.5), its computational requirements are relatively high. In order to reduce the computational load, we have several options:

1. **Reduce the number of samples taken each *switching_time*.** If we reduce the frequency which we get the number of users at each cell, we will have do less Erlang-B calculations.
    - The most extreme case is to only evaluate one sample each *switching_time* (Figure 4.5), doing the allocation of the channels based on the number of users at this time, not taking into account any user evolution over the time.

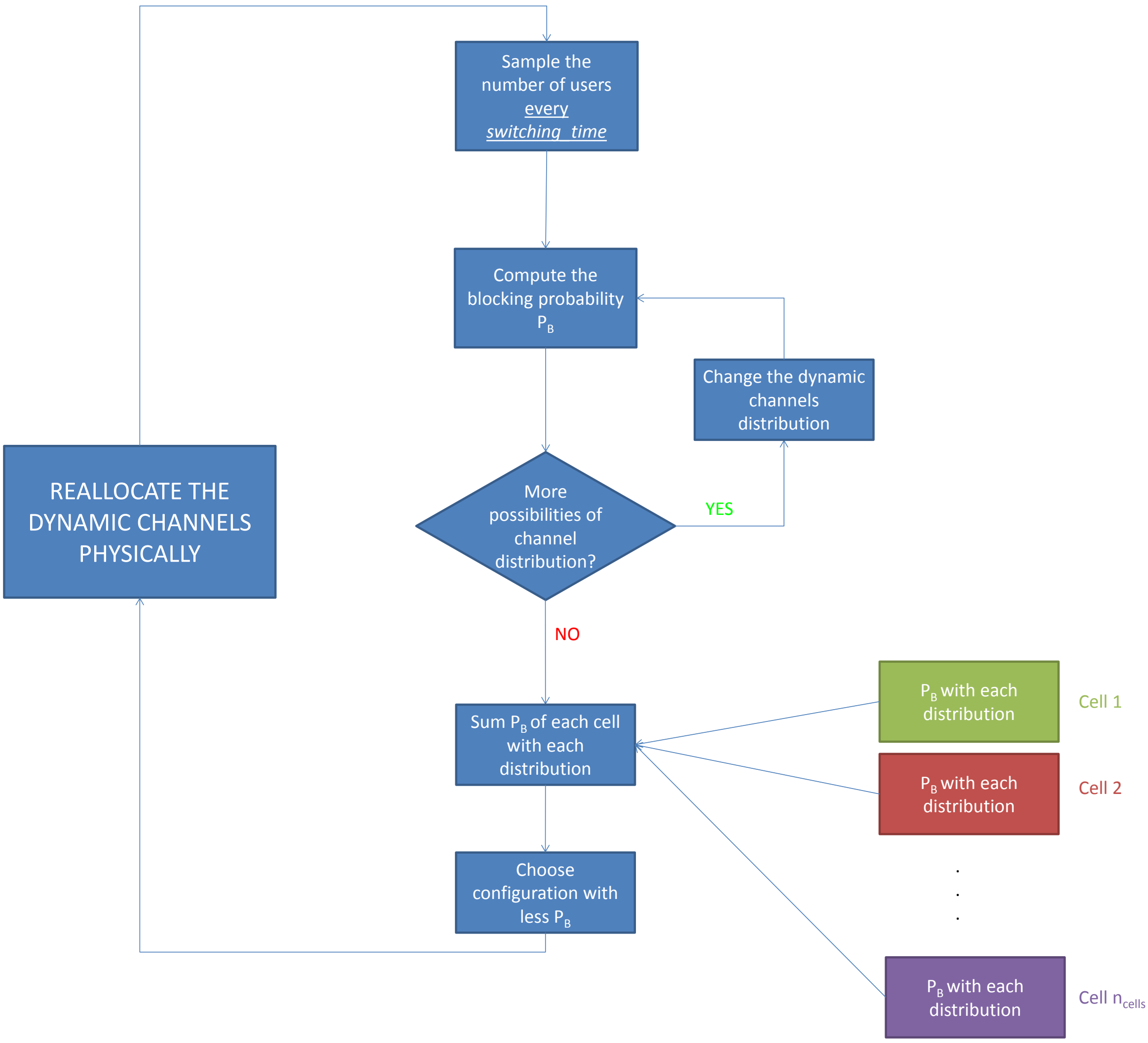

Figure 4.5. Modification of the algorithm 1. Take only one sample per switching_time slot.

2. **Study the network traffic changes.** If we make studies about the network traffic evolution in a certain period of time, and we compute the best channel allocation a posteriori, we can apply this configuration on future periods of time.
For example, we can study the best dynamic channel configuration with the data obtained in a day, save this configuration and apply the channel distribution obtained on same day of the subsequent week.
    - In this case, we have all the data stored. Thus, we will modify the algorithm to apply the best channel configuration to the current *switching_time* slot.

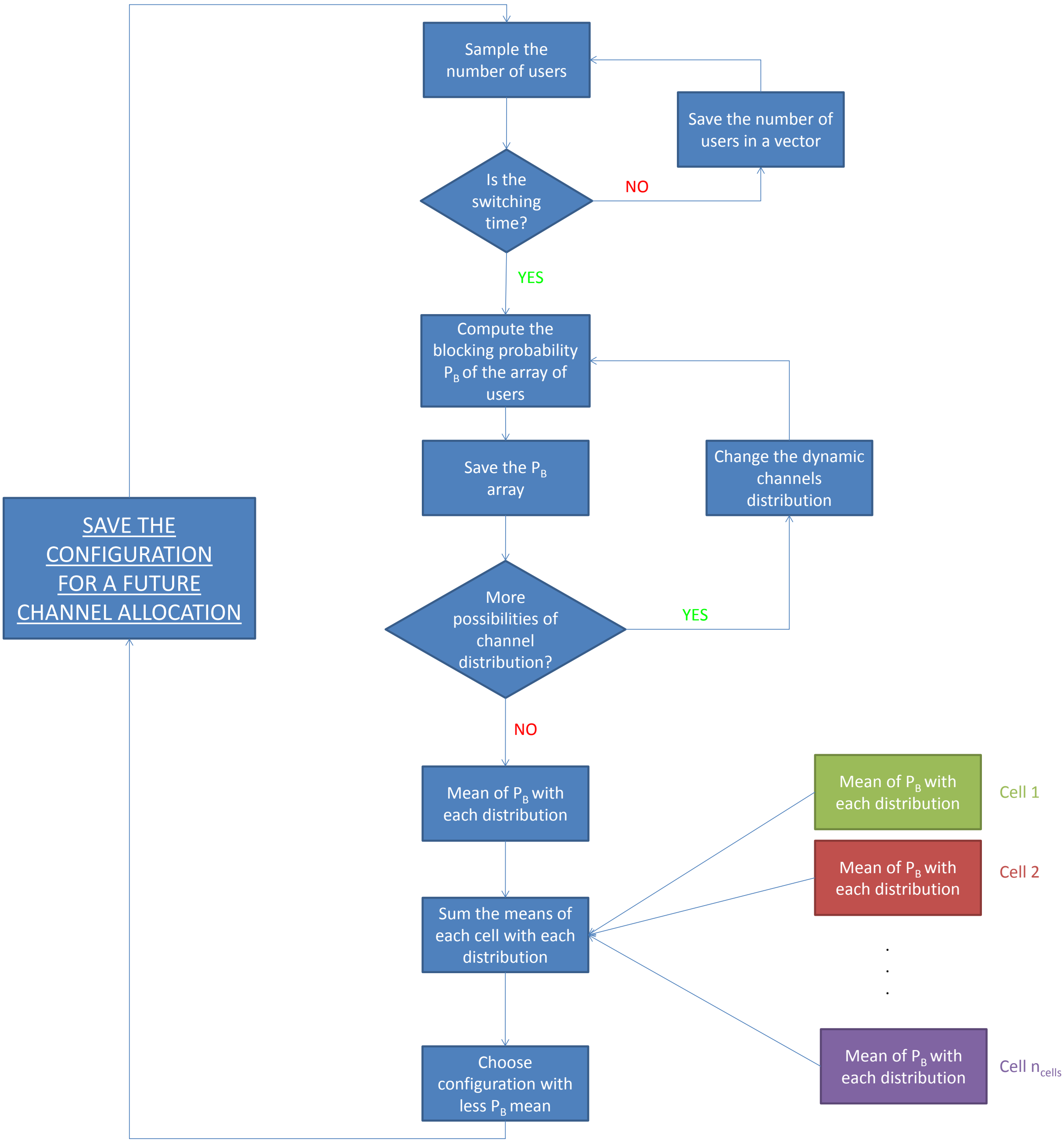

Figure 4.6. Modification of the algorithm 2. The algorithm is used to analyze stored data and apply the analysis to future channel allocations.

3. **Predict the number of users.** If we apply forecasting techniques to estimate the average number of users we will have in our *switching_time* slot, we will be able to find the best possible channel allocation to this forecasted value. The performance of this algorithm will vary depending on the performance of the prediction techniques.
   - One possible solution would be to apply *Machine Learning* techniques to predict the average number of users based on the previous average number of users extracted from real data [20].

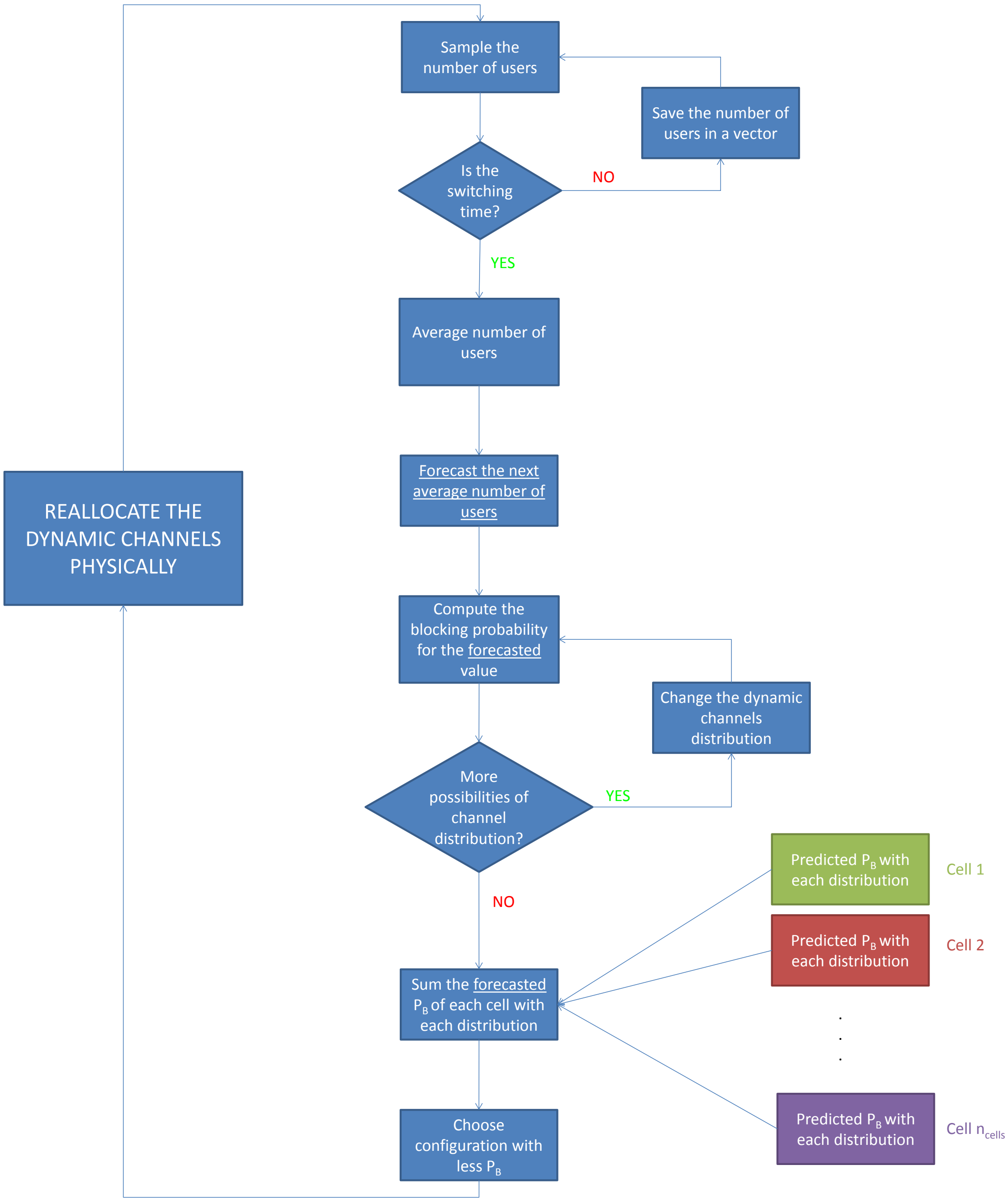

Figure 4.7. Modification of the algorithm 3. Apply prediction techniques to forecast the average number of users we will have in a switching_time slot

4.4 Queuing the new calls

In this section we present another possible procedure to reduce the blocking probability. It can be applied to already deployed networks; regardless they use FCA, DCA or HCA. We propose to combine our algorithm with queuing techniques to further reduce the blocking probability of the network.

If we consider the new calls and the handoff calls separately, we can queue either the new calls or the handoff ones in order to reduce the blocking probability. We will consider them as two independent processes with Poisson arrival rate.

We define a new call as a connection to the network of a user that was not previously connected. A handoff call is a connection to a cell of a user from a neighbor cell. It means that the connection ends at one cell and starts at the neighbor one.

In this example we have queued the new calls and not the handoff ones.

4.4.1 Theoretical analysis

Let us consider λ_n as the arrival rate of new calls and λ_h as the arrival rate of handoff calls. We can model the system as a Markov chain of $N + M_n$ states, where $\lambda = \lambda_h + \lambda_n$.

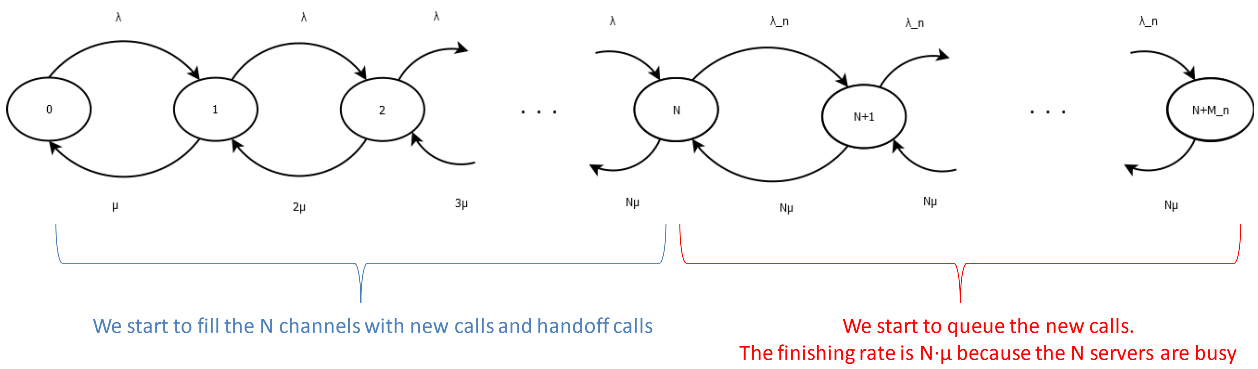

Figure 4.8. Markov chain for systems queuing the new calls

As we have defined before, the blocking probability is the probability of being at the highest possible state, where there are no servers available. Hence, the blocking probability of new calls is π_{N+M_n}, since in a lower state we are able to either process the call (if there are less than N users) or queue the call (if there are more than N users and less than M_n in the queue).

Since the system is stable, we can compute the probability at a certain state as the probability of being at its previous state multiplied by the arrival rate and divided by the finishing rate.

Thus,

$$P_{B_{new}} = \pi_{N+M_n} = \left(\frac{\lambda_n}{N\mu}\right)^{M_n} \cdot \pi_N \qquad (4.11)$$

We can do the same, and relate π_N with π_0

$$\pi_N = \frac{\lambda^N}{N! \cdot \mu^N} \cdot \pi_0 \tag{4.12}$$

As we have done before, we have to fulfill the condition (4.7) so

$$\begin{aligned}\pi_0 &= \left[\sum_{k=0}^{N} \left(\frac{\lambda}{\mu}\right)^k \cdot \frac{1}{k!} + \left(\frac{\lambda}{\mu}\right)^N \cdot \frac{1}{N!} \cdot \sum_{k=1}^{M_n} \left(\frac{\lambda_n}{N\mu}\right)^k\right]^{-1} = \\ &= \left[\sum_{k=0}^{N-1} \left(\frac{\lambda}{\mu}\right)^k \cdot \frac{1}{k!} + \left(\frac{\lambda}{\mu}\right)^N \cdot \frac{1}{N!} \cdot \sum_{k=0}^{M_n} \left(\frac{\lambda_n}{N\mu}\right)^k\right]^{-1} = \\ &= \left[\sum_{k=0}^{N-1} \left(\frac{\lambda}{\mu}\right)^k \cdot \frac{1}{k!} + \left(\frac{\lambda}{\mu}\right)^N \cdot \frac{1}{N!} \cdot \frac{1 - \left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1 - \left(\frac{\lambda_n}{N\mu}\right)}\right]^{-1}\end{aligned} \tag{4.13}$$

Coming back to (4.12), we can express it as

$$\pi_N = \frac{\lambda^N}{N! \cdot \mu^N} \cdot \pi_0 = \frac{1}{N! \cdot \sum_{k=0}^{N-1} \left(\frac{\lambda}{\mu}\right)^{k-N} \cdot \frac{1}{k!} + \frac{1 - \left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1 - \left(\frac{\lambda_n}{N\mu}\right)}} \tag{4.14}$$

So the blocking probability of new calls is

$$P_{B_{new}} = \pi_{N+M_n} = \left(\frac{\lambda_n}{N\mu}\right)^{M_n} \cdot \pi_N = \frac{\left(\frac{\lambda_n}{N\mu}\right)^{M_n}}{N! \cdot \sum_{k=0}^{N-1} \left(\frac{\lambda}{\mu}\right)^{k-N} \cdot \frac{1}{k!} + \frac{1 - \left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1 - \left(\frac{\lambda_n}{N\mu}\right)}} \tag{4.15}$$

Regarding the handoff calls, the loss probability (dropping) is the probability of not having available servers, regardless the number of new calls that are queued. Hence, the dropping probability of the handoff calls will be the probability of being at a state equal or higher to N.

$$P_{D_{hand}} = \sum_{k=N}^{N+M_n} \pi_k \tag{4.16}$$

Applying the same stability criterion as in (4.11),

$$\sum_{k=N}^{N+M_n} \pi_k = \sum_{k=0}^{M_n} \left(\frac{\lambda_n}{\mu}\right)^k \cdot \pi_N = \frac{1-\left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1-\left(\frac{\lambda_n}{N\mu}\right)} \cdot \pi_N \tag{4.17}$$

By replacing (4.14) in (4.17):

$$P_{D_{hand}} = \frac{1-\left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1-\left(\frac{\lambda_n}{N\mu}\right)} \cdot \frac{1}{N! \cdot \sum_{k=0}^{N-1}\left(\frac{\lambda}{\mu}\right)^{k-N} \cdot \frac{1}{k!} + \frac{1-\left(\frac{\lambda_n}{N\mu}\right)^{M_n+1}}{1-\left(\frac{\lambda_n}{N\mu}\right)}} \tag{4.18}$$

4.4.2 Simulation when queuing

In order to see the theoretical results of Section 4.4.1 in a graphic way, we have performed a simulation in MATLAB. The simulation is valid for only one cell, and the number of users is not random but increasing from 0 to 100 users.

The number of servers is 15, all of them fixed, and the size of the queue is 10 users. Since we have modeled both types of incoming calls as independent processes, to make the graphics clear, when we are analyzing the new calls we have fixed the number of handoff users in the cell at 50, and vice versa for the handoff calls. This is just because making sweeps of two variables might make the graphic unclear.

In Figure 4.9 and Figure 4.10 we can observe that a reduction of the blocking probability is always done when queuing the new calls.

The results are the same if the queue is done at the handoff calls and we drop the new calls. If we did a queuing of both types of call, the system would become very difficult to analyze and it becomes beyond the scope of this document. Our purpose is to show that this is a practical way to reduce the blocking probability. However, to integrate both queues with our algorithm could be an interesting future work to consider.

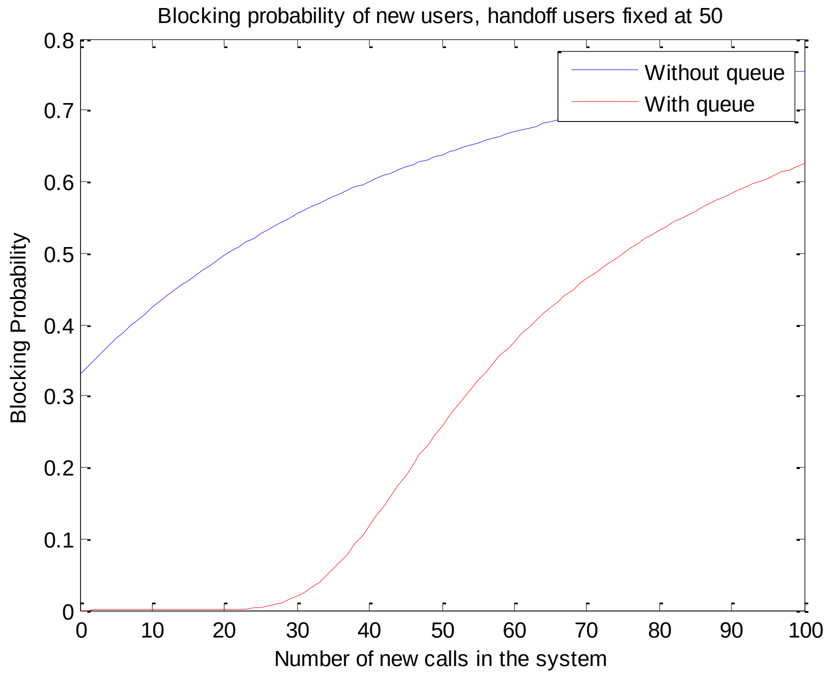

Figure 4.9. Blocking probability over time for new calls

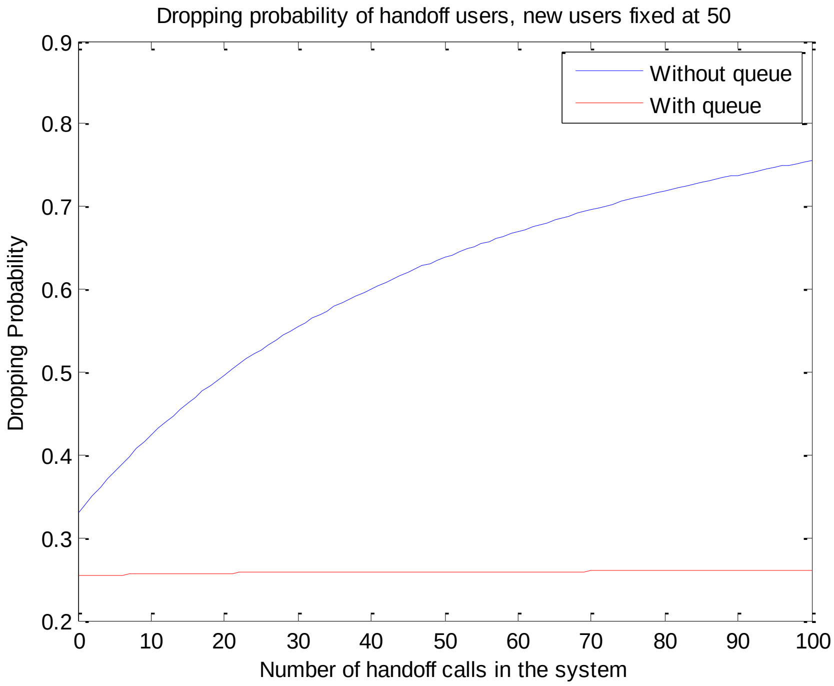

Figure 4.10. Blocking probability over time for handoff calls

5
Simulation results

In order to assess the performance of the algorithm proposed in Section 4.3, several simulations with MATLAB have been run. The simulations show us the blocking probability comparison between the two different techniques we assess, FCA and HCA. A statistical study to check the reduction of P_B have been also done.

5.1 Simulation setup

For all the simulations run, we set several general parameters related to the architecture of the network:

- 2 or 3 cells, depending on the simulation
- Number of fixed channels per cell higher than zero
- Total number of dynamic channels per cell, reconfigurable by the algorithm explained in Section 4.3
- Each channel handles 8 servers (8 users)
- Switching time of 3 minutes and 20 seconds (200 sec)

Regarding the utilization of the network,

- Random number of users N_{users} with an initial seed of 100 users per cell
- Total arrival rate depending on the number of users of the system
- Finishing rate of $\mu = 0{,}1$ calls/second
- Total simulated time of 33 minutes and 20 seconds (2000 sec)

One problem with the simulations was the limitation of the number of channels that we were able to introduce. As the reader may know, for calculating the blocking probability we used the Erlang-B formula (4.9). This means that we had to do a factorial operation. The maximum integer number that MATLAB does not approximate by ∞ is (170!). Knowing that we simulated 8 servers/channel, the maximum number of channels that we could have in a cell was 21. So the summation of fixed + dynamic channels was always below 21.

All the simulations have been run in a Windows 7-equipped computer (Intel® Xeon® CPU W3550 @ 3.07 GHz with 6.0 GB RAM Memory). The MATLAB version was MATLAB R2013b.

5.2 HCA 11:5 with 2 cells

The first test was done with 2 cells, with 11 fixed channels per cell and 10 dynamic channels to distribute between the two cells. Hence, in total we had 32 channels.

The generated random number of users is shown in Figure 5.1.

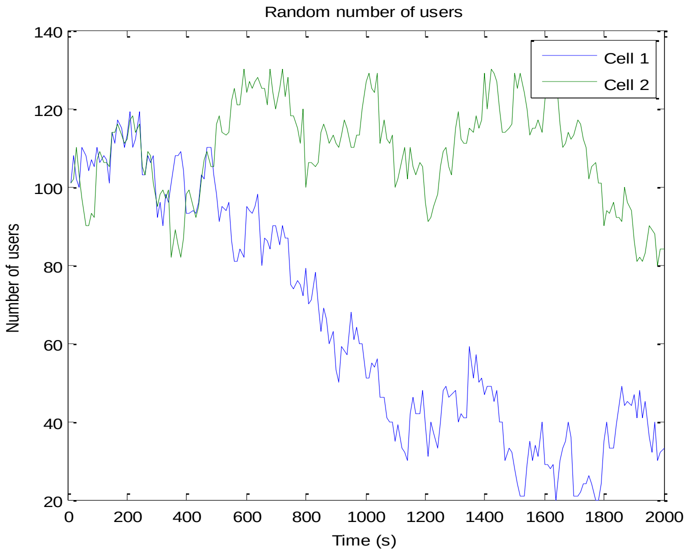

Figure 5.1. Random number of users for HCA 11:5 test

If we use the Fixed Channel Allocation technique, i.e. we allocate 11 fixed + 10/2 dynamic = 16 channels per cell, the result shows that the blocking probability in the second cell is much higher than in the first one (Figure 5.2).

Comparing to HCA technique, Figure 5.3 shows a huge reduction of P_B in the second cell from $t = 800\ s$. This means that from $t = 800\ s$ until the end, more channels have been assigned to cell 2 in order to reduce the total blocking probability of the system.

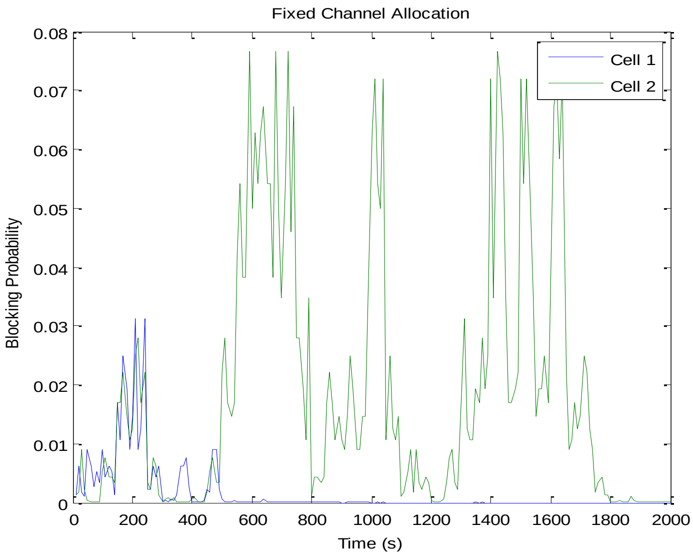

Figure 5.2. Blocking probability over time for FCA

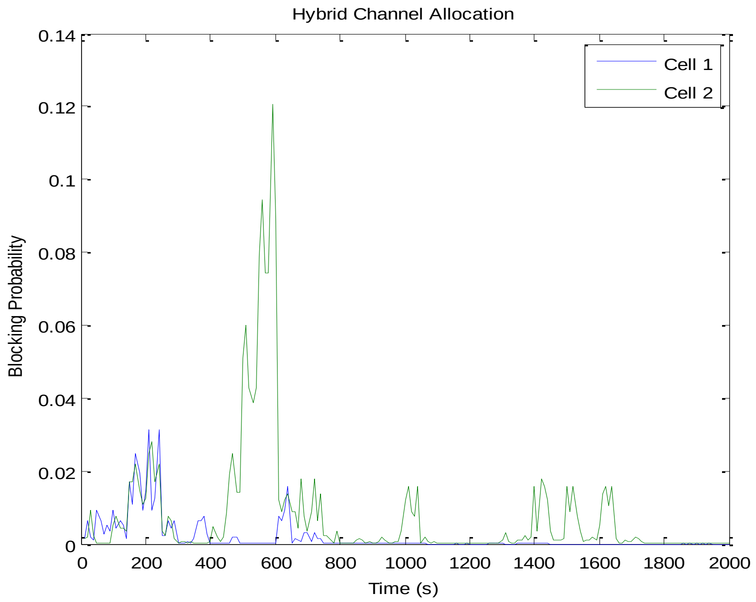

Figure 5.3. Blocking probability over time for HCA 11:5

In Figure 5.5 we can see the constant reduction from $t = 800\,s$ we have already mentioned, comparing the blocking probability in the second cell by applying FCA or HCA.

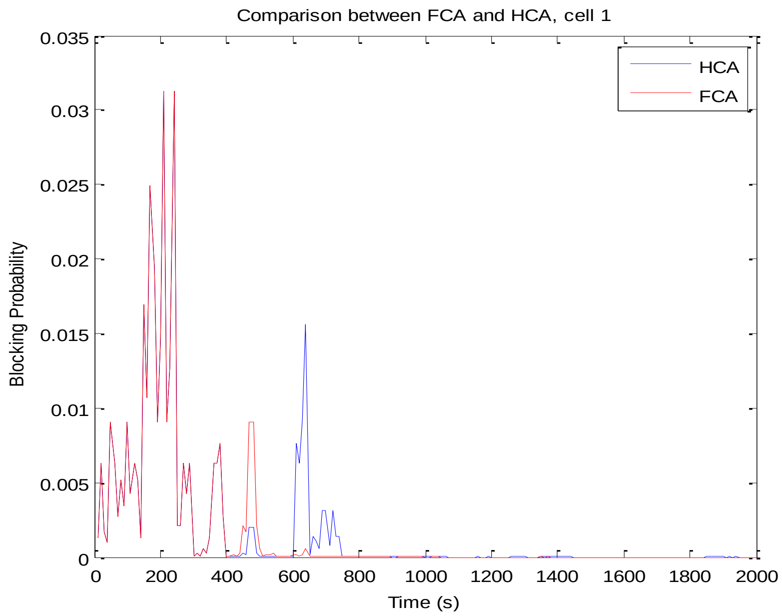

Figure 5.4. Blocking probability with FCA and HCA for cell 1

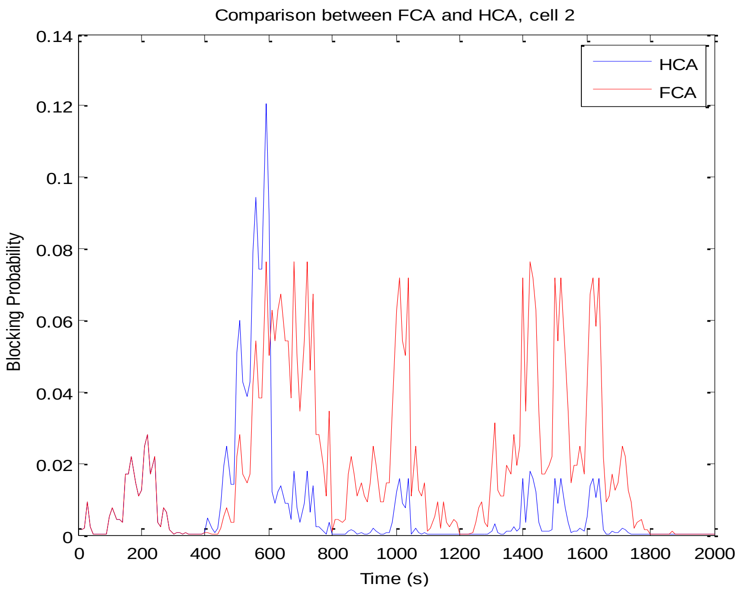

Figure 5.5. Blocking probability with FCA and HCA for cell 2

The blocking probability mean with FCA is 1.03%, whereas with HCA is 0.475%. This is a reduction of 53.6% of the total blocking probability.

5.3 HCA 5:8 with 2 cells

In order to check the performance with a different ratio of fixed channels versus dynamic channels, we did a test with 5 fixed channels per cell and 16 total dynamic channels.

Figure 5.6 shows the distribution of the users among cells.

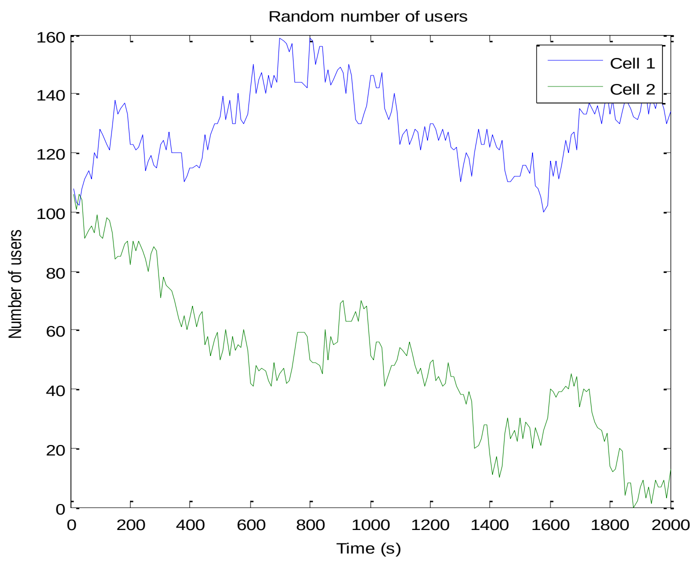

Figure 5.6. Random number of users for HCA 5:8 test

Figure 5.7 and Figure 5.8 show that the shape of the blocking probability with the two techniques is similar. However, from $t = 400\ s$ until the end we observe a continuous reduction in the first cell. This is because with HCA there are more dynamic channels allocated in the first cell than with FCA.

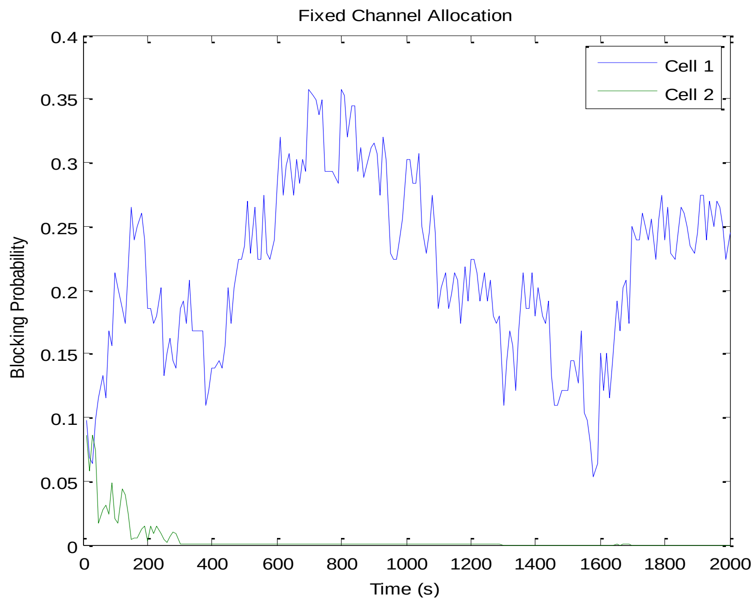

Figure 5.7. Blocking probability over time for FCA

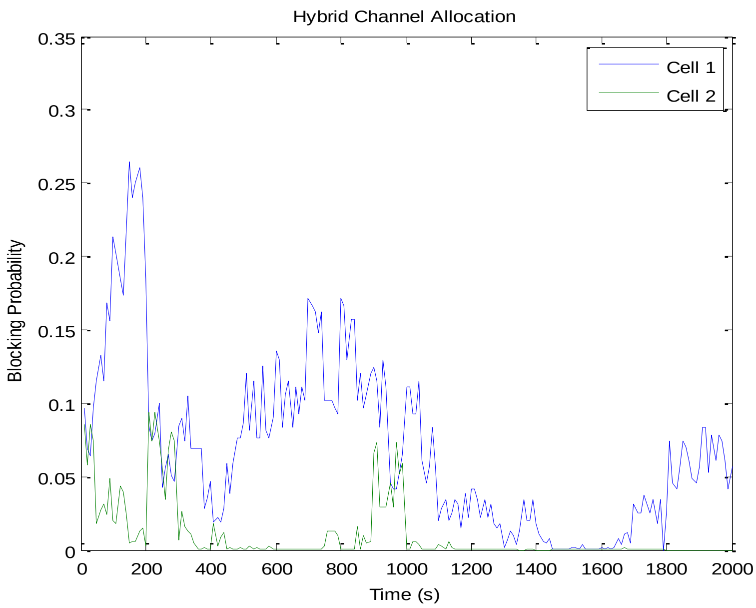

Figure 5.8. Blocking probability over time for HCA 5:8

We can observe in all the tests run that from $t = 0$ to $t = 200\ s$ both techniques have exactly the same blocking probability. The reason for this behavior is that at the beginning of the simulation we do not have prior information about the number of users in the previous *switching_time* slot, so instead of allocating the channels blindly, we use the FCA distribution.

In Figure 5.10 we can observe a high increase of P_B from $t = 800\ s$ to $t = 1200\ s$ at the second cell. The total blocking probability remains lower than the fixed one, though.

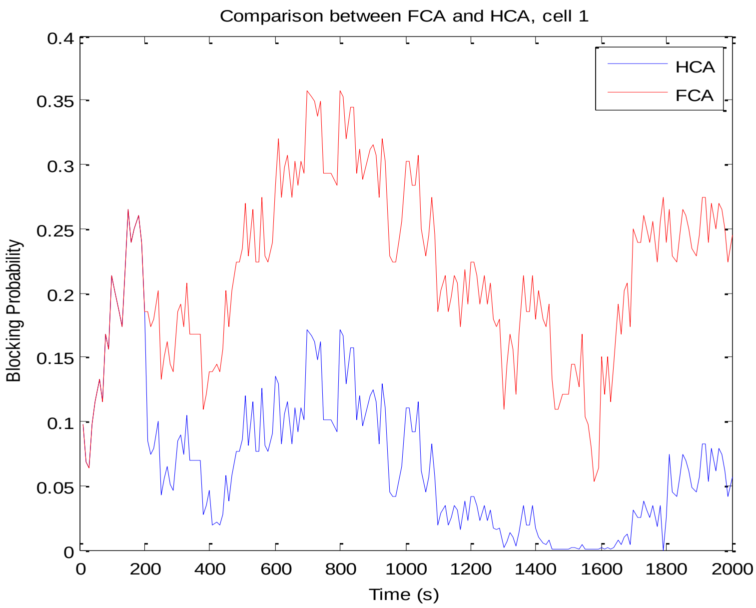

Figure 5.9. Blocking probability with FCA and HCA for cell 1

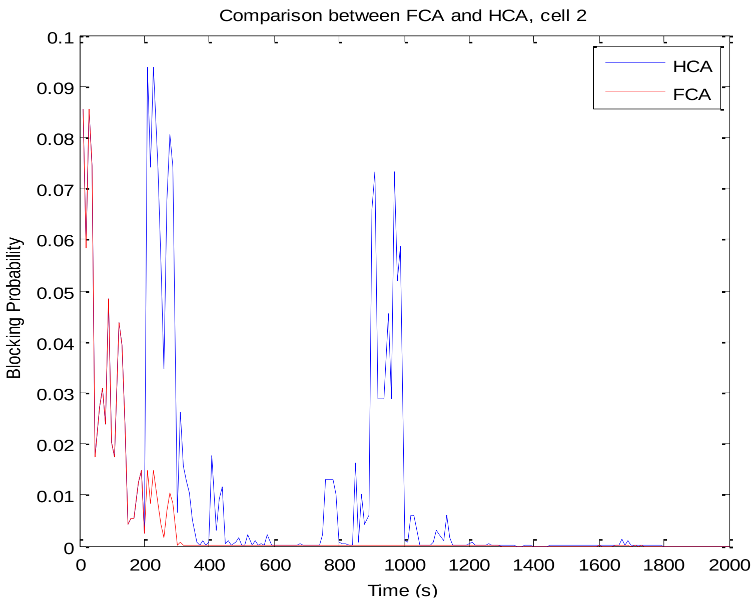

Figure 5.10. Blocking probability with FCA and HCA for cell 2

The blocking probability mean with FCA is 10.9%, whereas with HCA is 3.9%. This is a reduction of the 63.95% of the total blocking probability.

5.4 HCA 6:5 with 3 cells

The last test we want to show is the simulation of a system with 3 cells. The algorithm here becomes more difficult, and the simulation time longer. We made a test with 6 fixed channels per cell and 15 dynamic channels to be distributed among 3 cells.

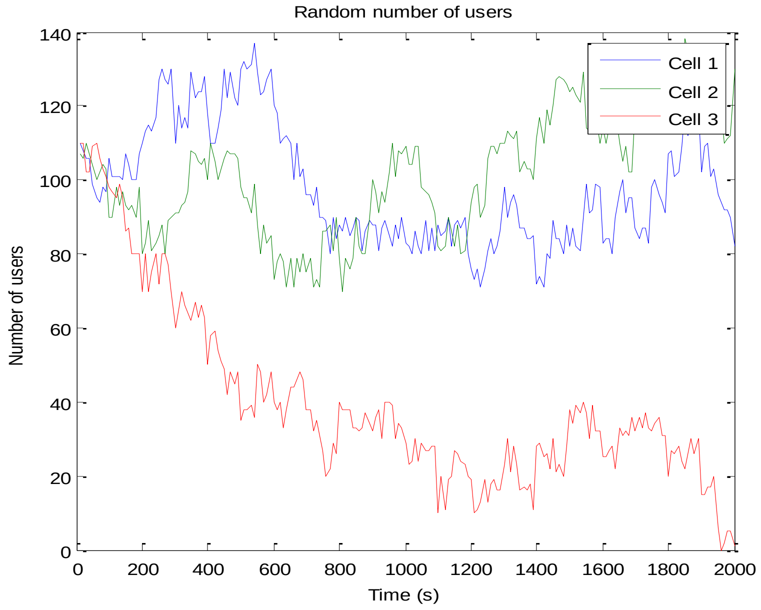

Figure 5.11. Random number of users for HCA 6:5 test

It can be seen here that the MATLAB limitation in the number of channels (see Section 5.1) makes the blocking probabilities higher.

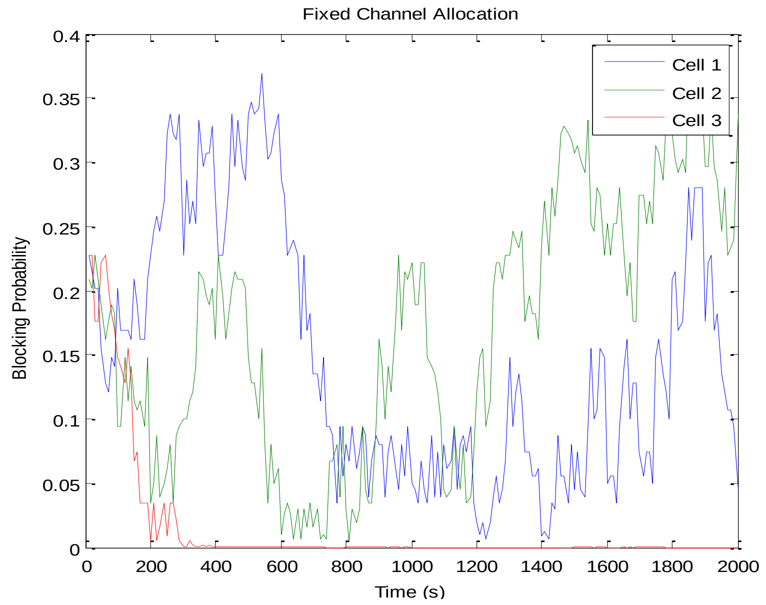

Figure 5.12. Blocking probability over time for FCA

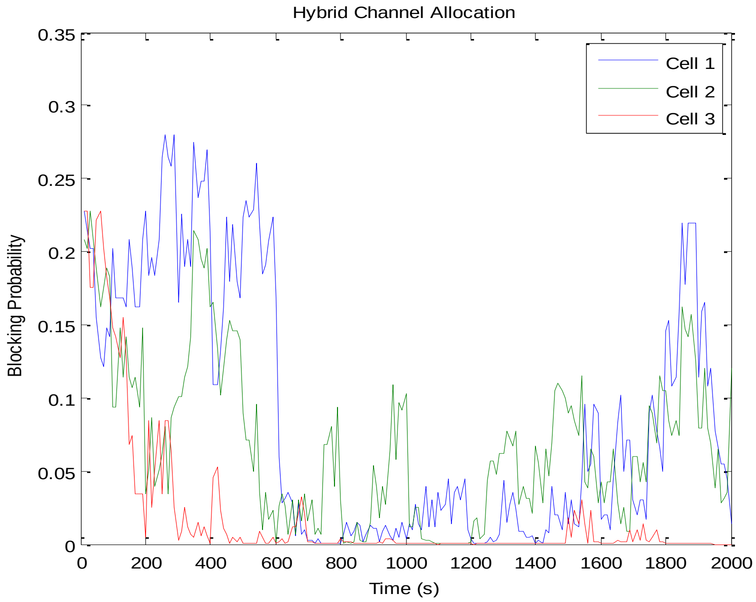

Figure 5.13. Blocking probability over time for HCA

We can see that the performance with 3 cells follows the behaviour observed with 2 cells. We have continuous reduction in the first 2 cells by taking some channels out from the third one, as seen in the Figure 5.16, where the blocking probability increases in order to have a reduction on the other cells.

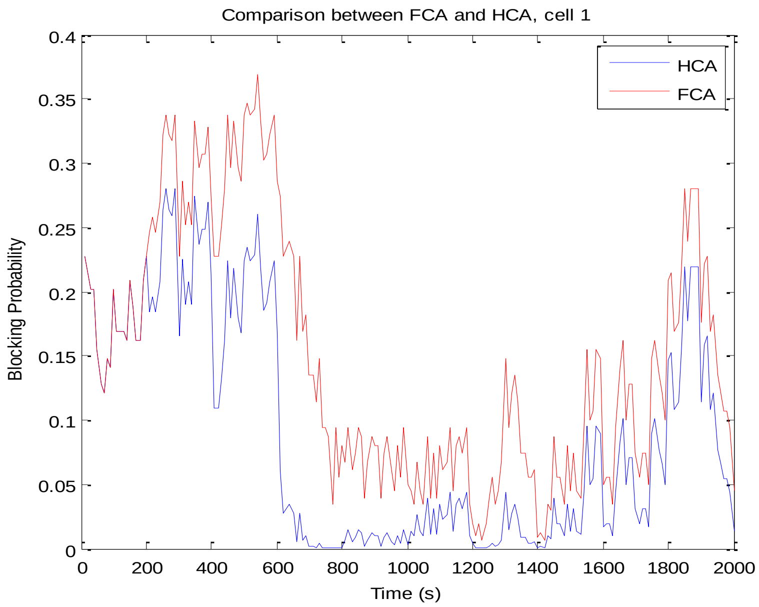

Figure 5.14. Blocking probability with FCA and HCA for cell 1

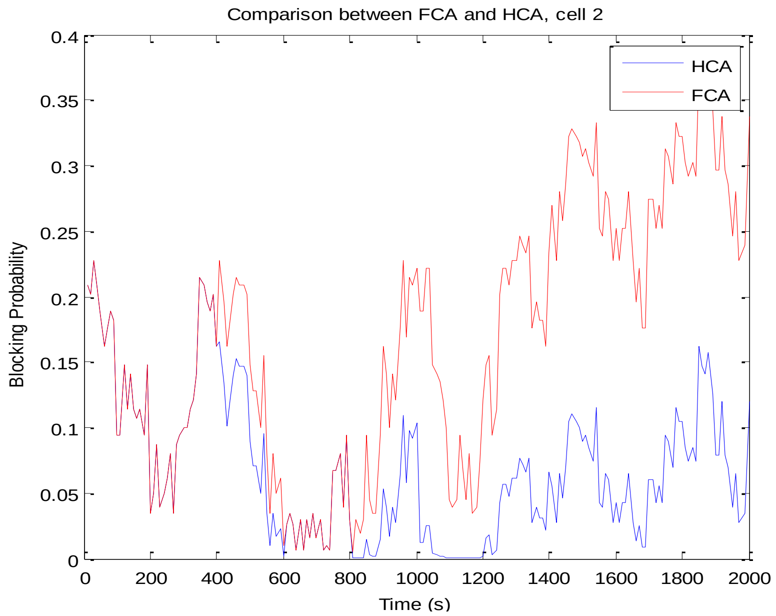

Figure 5.15. Blocking probability with FCA and HCA for cell 2

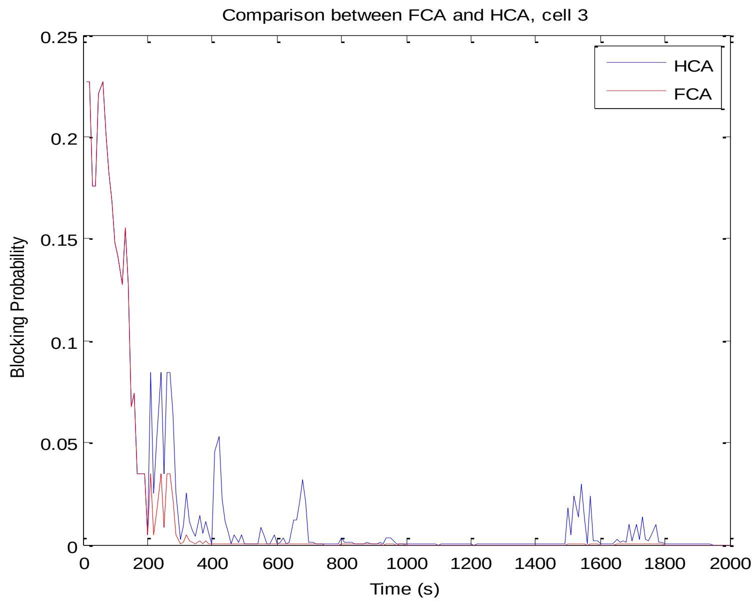

Figure 5.16. Blocking probability with FCA and HCA for cell 3

The blocking probability mean with FCA is 11.1%, whereas with HCA is 5.8%. This is a reduction of the 47.43% of the total blocking probability.

5.5 Statistical performance of the algorithm

In order to assess the performance of our algorithm in terms of reduction of blocking probability, we made a statistical analysis to quantify the percentage of reduced blocking probability.

The reduced percentage was calculated as:

$$\%_{red} = \left(1 - \frac{P_{B_{HCA}}}{P_{B_{FCA}}}\right) \cdot 100 \tag{5.1}$$

Where $P_{B_{HCA}}$ is the blocking probability using HCA technique and $P_{B_{FCA}}$ is the blocking probability using a fixed distribution of channels. The tests were done with the same parameters than the ones stated in Section 5.1, with the following particularities:

- 2 cells
- Random number of users N_{users} without initial seed
- 1000 runs of the defined network, each run with a new random generation of users

We did two tests. The first one with 7 fixed channels per cell and 2 dynamic, so 16 channels in total. We can see the histogram of $\%_{red}$ depicted in Figure 5.17

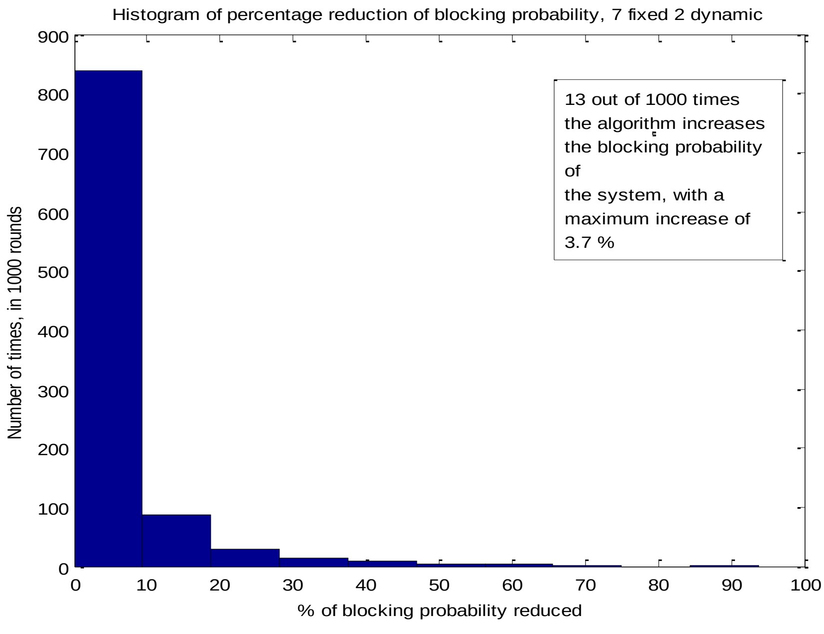

Figure 5.17. Histogram of percentage of blocking probability reduction with HCA 7:1

838 out of 1000 times, the percentage of reduction is less than 10 %. The reduction of the blocking probability is relatively low because the rate of fixed to dynamic channels is very big, i.e. we have only 2 dynamic channels to change.

13 of the 1000 tests the results were unsatisfactory, having in the worst case an increase of the blocking probability of 3.7% in relative terms. This means that in 13 times,

the allocation of the dynamic channels with the HCA technique was worse in than with FCA. Thus, we do not always ensure a better performance with HCA than with FCA.

On the second test, we chose 1 fixed channel per cell and 14 dynamic channels, so the same number of total channels than in the previous test.

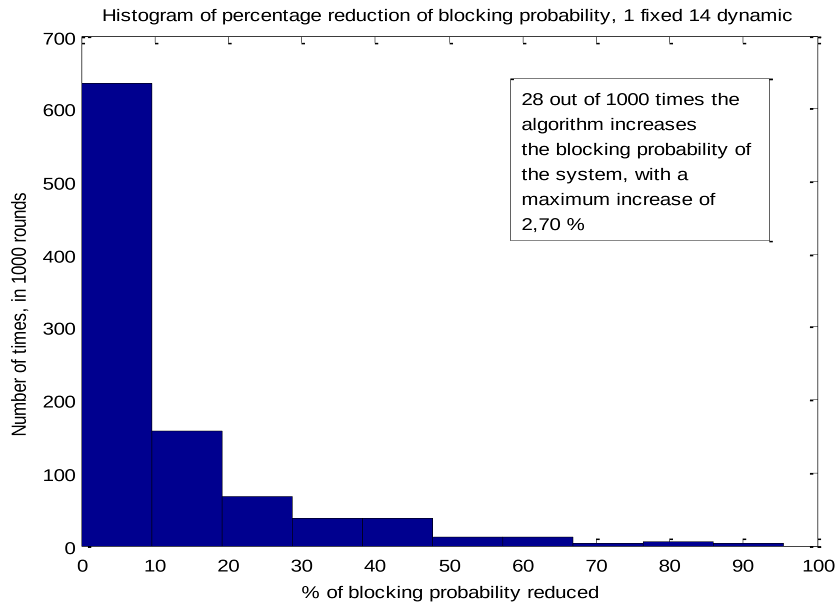

Figure 5.18. Histogram of percentage of blocking probability reduction with HCA 1:7

Figure 5.18 shows a better performance than the previous test, as the rate of fixed channels versus dynamic channels is lower. This behavior is expected, as we have more possibilities to allocate channels than in the previous statistical test. The mean value of $\%_{red}$ is 11.52%.

In this case, 28 out of 1000 times the HCA technique was worse than the FCA one.

5.5.1 Statistical reduction analysis

There is a tradeoff between the ratio fixed channels vs. dynamic channels and the simplicity of the system. The more dynamic channels, the higher the reduction of the blocking probability is.

However, with a high number of dynamic channels the simplicity of the system is lower. If we have a lot of dynamic channels and a lot of cells, the computational time can be very high, and could be even higher than the switching time. Then, the algorithm would introduce a non-desired delay.

Moreover, with a higher amount of dynamic channels, the number of handover procedures would also increase. This means that layers of the OSI-ISO would have also more work load.

Figure 5.19 shows the computing time of the HCA procedure by changing the ratio of fixed versus dynamic channels in a simulation of 20 channels distributed among 2 cells. As expected, the computational time increases when the number of dynamic channels increases.

Therefore, the number of dynamic channels that we can put in the network is limited by some factors, but the algorithm ensures a reduction of the blocking probability of the whole network.

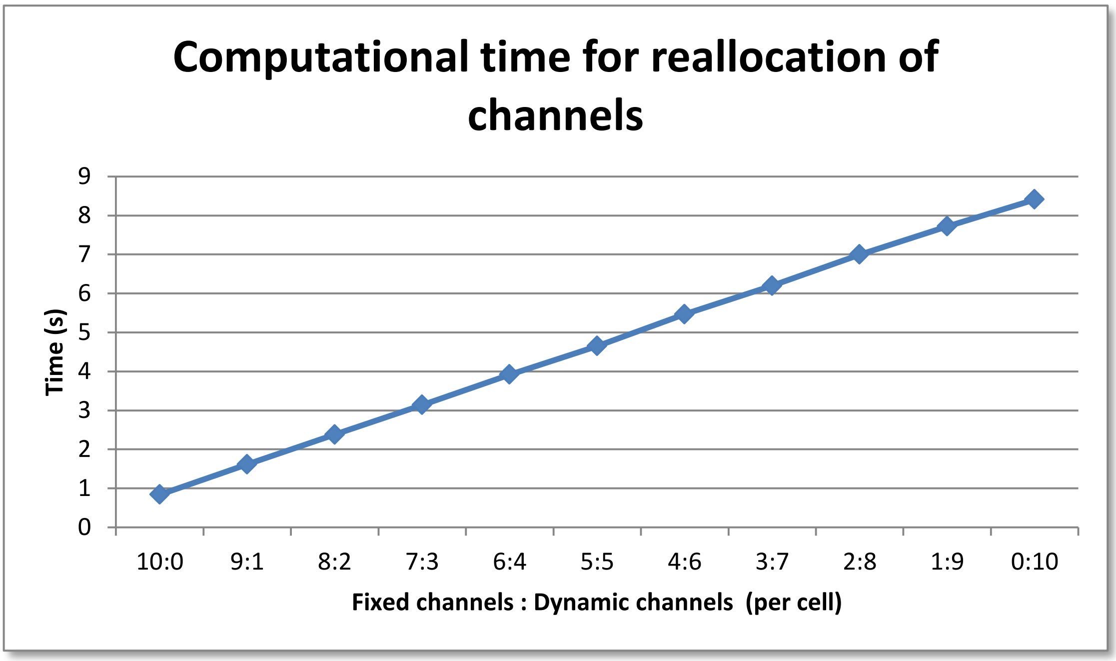

Figure 5.19. Computational time with different channel allocations in a 20-channel test with 2 cells

6
Experimental results

Although the main work load of this thesis included theoretical and simulation analysis, several results have been obtained in the laboratory for future experimental tests related with the thesis.

We wanted to do more experiments in the lab, but necessary equipment such as a PPG or an envelope detector was not available.

6.1 Experimental setup

The optical switch we have worked with is a MEMS-based optical switch. Inside the MEMS switching, the switch chosen is made of tilting micromirrors technology. The reason for choosing an optical MEMS switch is because this type of switch offers a good tradeoff between the price and the switching speed or the insertion loss [17]. Moreover, it has the advantage of mechanical stability.

As mentioned, the switch used is a MEMS-based fast optical switch, with a single input and 8 outputs. The switch chosen is *SW 1x8* from *Sercalo* manufacturer [21]. The most important features are that it allows a switching speed below 1 ms and it has insertion losses less than 1.6 dB. The other features are summarized in Table 6.1.

TECHNICAL SPECIFICATIONS – SERCALO SW 1X8				
	Unit	**Min**	**Typ**	**Max**
SWITCH				
Wavelength Range	nm	1240		1640
Insertion Loss	dB		1.2	1.6
Crosstalk	dB		75	60
Backreflection	dB		55	45
Polarisation Dependent Loss	dB			0.12
Switching Time	ms		0.5	1
Switching Voltage	V			5
Fiber Pigtail	µm		9/125/900	
Durability	cycles		no wear out	
PACKAGE				
Power Consumption	mW		40	
Operation Temperature	ºC	0		70
Storage Temperature	ºC	-40		85
Size (L x W x H)	mm		76 x 93 x 9.5	

Table 6.1: Technical specifications of Sercalo SW 1x8

In order to see whether the switch could work in a real environment, a checking of the technical specs provided by the manufacturer was done. For testing the optical switch a control board designed by Marti Sales was used [10]. It allows the selection of the output with a manual toggle, all done in the electrical domain by logical electronics.

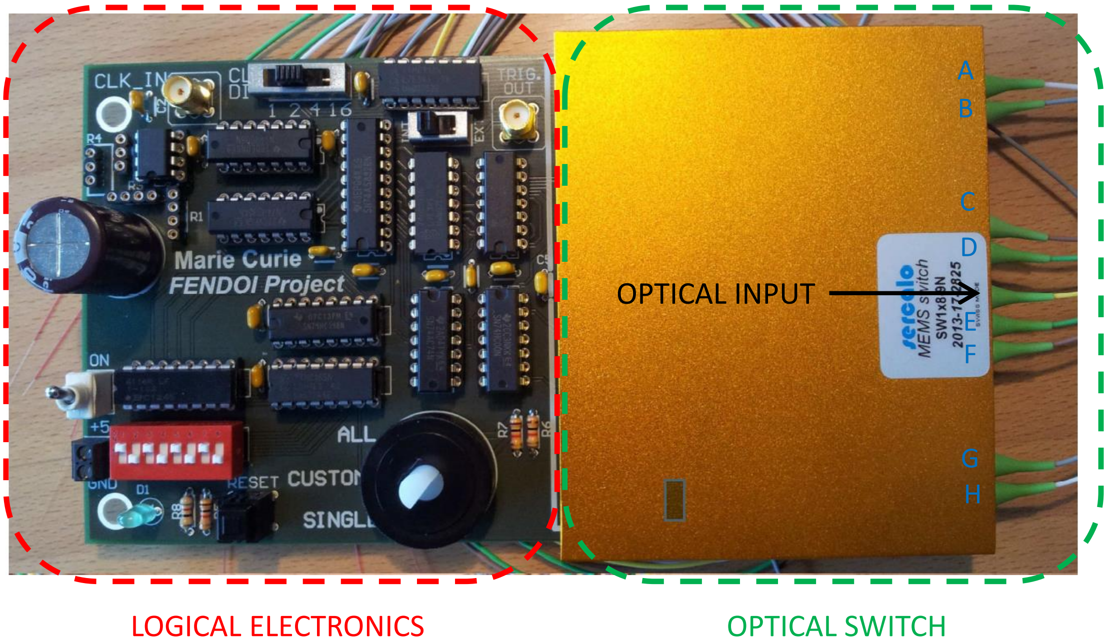

Figure 6.1. Optical switch Sercalo SW 1x8 with its test board. A-H: optical outputs of the switch

The most important parameter for a DCA-based network is the optical Insertion Loss, since the switching time for changing the channels will be higher than 1 ms. Therefore, we checked the optical losses with the setup depicted in Figure 6.2.

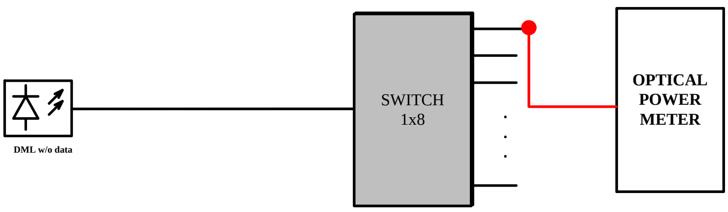

Figure 6.2. Experimental setup for the static characterization of the switch

A Directly Modulated Laser (DML) was used for the generation of the lightwave, since it is a very simple technology to modulate the data for future experiments. For connecting the DML and the power meter to the switch, we did a splicing of the input and outputs of the commercial switch.

6.2 Experimental results

The results released from the tests of the optical insertion losses are depicted in Figure 6.3:

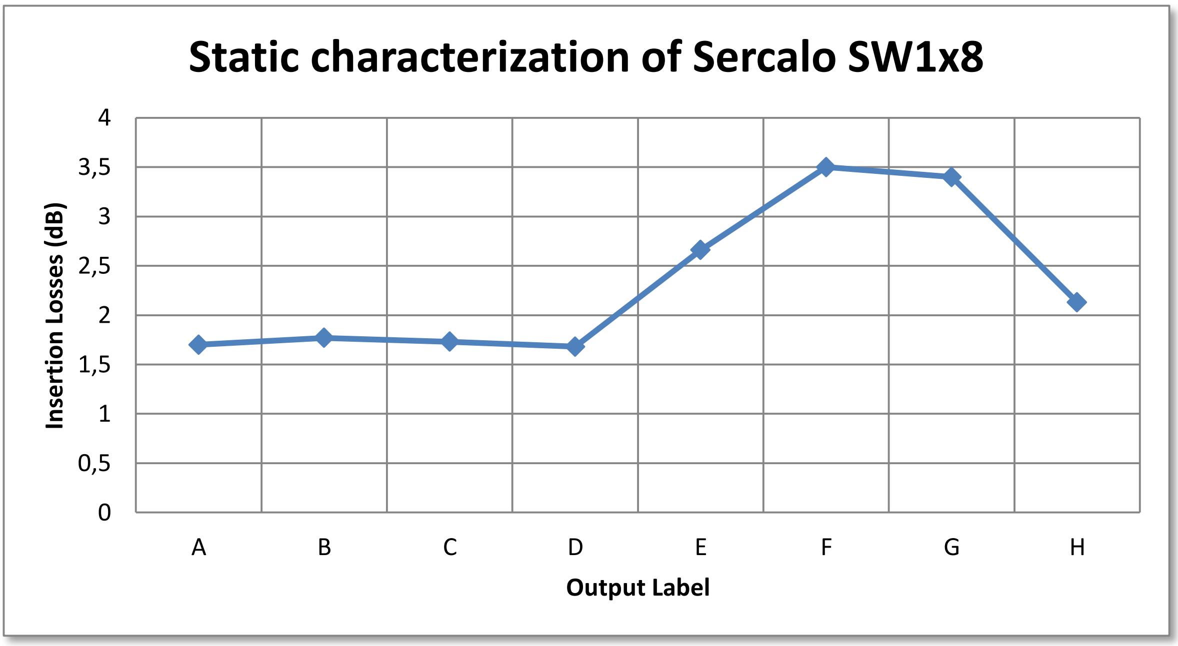

Figure 6.3. Static characterization of the employed optical switch

We can observe that the losses are quite similar in all the outputs but outputs E, F and G. This misleading with the datasheet value may be due to either fabrication or splicing losses. Although all the spliced fibers at the outputs and input were done with estimated optical losses below 0.5 dB, the losses were an estimation provided by the splicer machine, not the real loss value. The fiber, connectors, etc. may also have introduced some losses to the system.

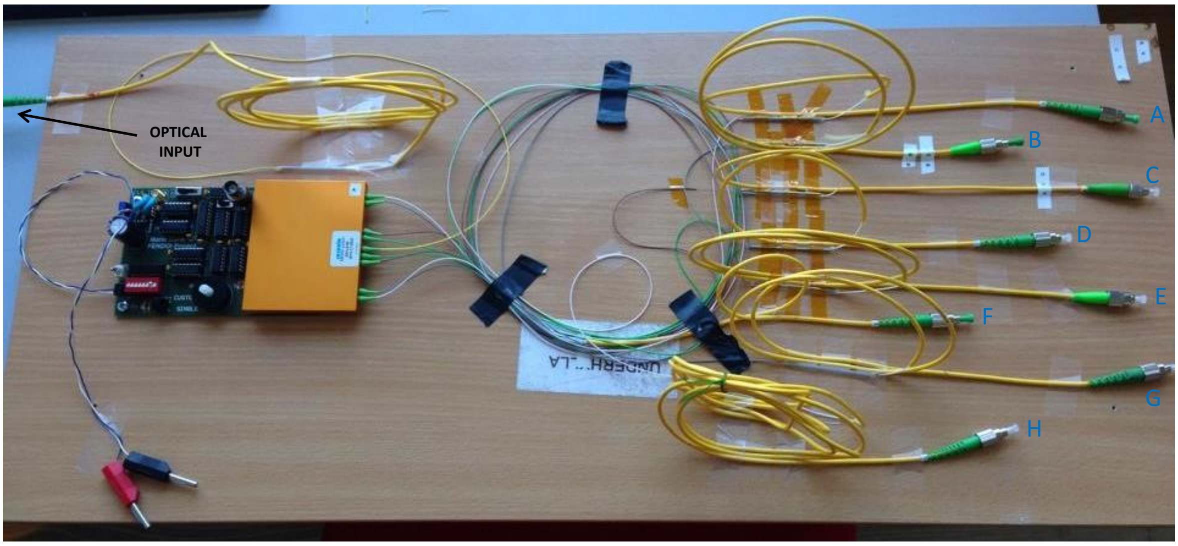

Figure 6.4. Test board with Sercalo SW1X8 and connectors at the outputs A-H

7 Conclusions

We need a solution for next generation wireless networks in order to be able to provide high-capacity links. In this thesis we have studied a solution for next-generation access networks based on the migration to mm-wave frequency range and the use of Radio-over-Fiber technologies. Furthermore, different techniques of channel allocation have been discussed and compared.

A novel algorithm based on the Hybrid Channel Allocation technique has been developed and tested with 2 and 3 base stations.

Three tests of 2000 seconds each have been run, showing an effective reduction of the blocking probability in the whole network of 53.6 %, 47.4 % and 63.9 %. A statistical quantification of the relative reduction of the blocking probability when applying our algorithm has been also presented.

The algorithm ensures a reduction of the blocking probability in a 97% of the times it is applied. The statistical analysis shows a tradeoff between the dynamic channels putted in the network and the computing time of the channel reallocation. Hence, in a real implementation, the decision of the ratio fixed versus dynamic channel should be studied for each particular network.

We have also characterized an optical switch for a possible future remote node in order to perform HCA in future experiments. The switch provided insertion losses below 2 dB for each channel on average. These results enable a future construction of a Remote Node performing a Hybrid Channel Allocation.

The experimental demonstration of the feasibility of the algorithm is therefore open for future work.

7.1 Future work

Since the work done so far covers several engineering fields, it opens plenty of possibilities for future work

- Test a mm-wave (60 GHz) RoF link with the characterized commercial switch.
- Test a WDM system with a remote node based on the characterized commercial switch.

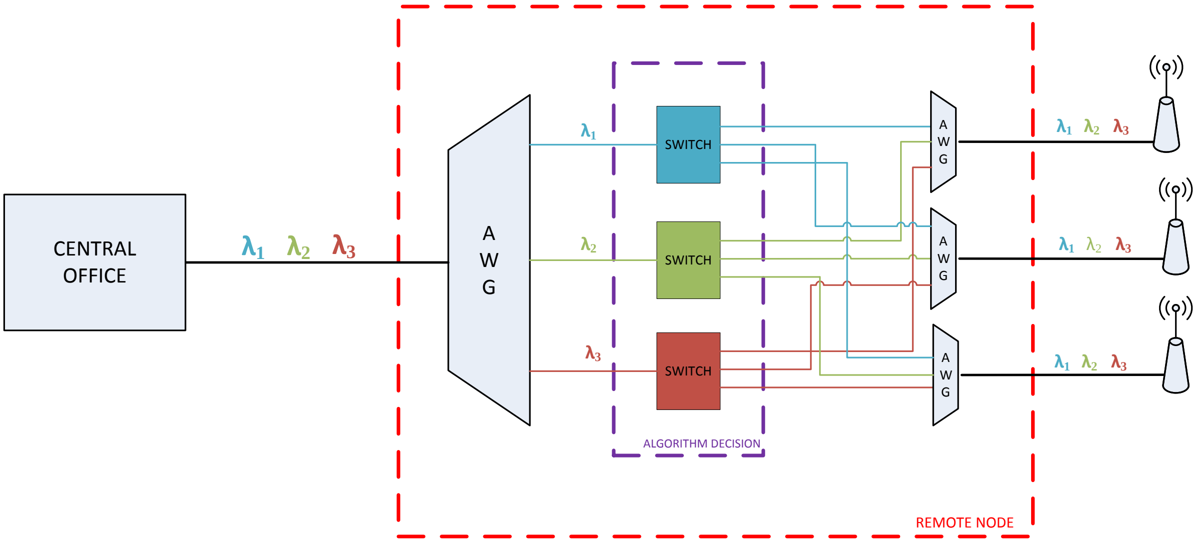

Figure 7.1. Future experimental setup for a WDM system transmission for 3 BSs. AWG: Arrayed Waveguide Grating

- Make simulations of the algorithm with higher number of cells and real traffic profiles.
- Integrate the proposed channel allocation algorithm with other channel allocation procedures which take into account issues such as frequency reuse or interferences.
- Reprogram the algorithm with electrical outputs and make an electrical control board for *Sercalo SW1x8* with channel reallocation capability.

8
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