UPC – Tsinghua University

DYNAMIC BASE STATION ENERGY SAVING WITH RELAYS

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Nowadays one of the major worldwide concerns is the increasing energy consumption that is currently going on and its effect on the environment. The European Commission (EC) has reached an agreement to cut greenhouse gas emissions by 20% by 2020 and to improve energy efficiency by 20% [1]. One of the industries which is experimenting a bigger growth is the ICT industry, especially in emerging economies such as China, India or Brazil. Even though the ICT industry has helped reduce the human impact on nature, for example, by reducing the worldwide travelling of people thanks to teleworking or videoconferencing, or by helping to more precisely monitor parameters such as temperature, sun light and humidity using wireless sensor network technology to optimize the energy management in buildings, it is also responsible for an increasing percentage of the world energy consumption. According to the SMART 2020 study [2], the ICT industry accounted for 530 Megatons of CO_2 in 2002 and 830 Megatons in 2007. This means that the ICT industry is responsible for approximately 2 to 10% of the world energy consumption [3][4], and produces more CO_2 emissions than the aviation industry [5]. For example, Telecom Italia consumed more than 2TWh in 2007, 1% of Italian national energy demand [6] and in China, around 600.000 BSs were deployed in 2007 which consume as many as 20 billion KWh [7]. Within ICT, the contribution of mobile communication networks was 64 Megatons of CO_2 in 2002 and is expected to grow to about 178 Megatons in 2020.

Cellular networks consist of mainly three parts: the core network, taking care of the switching, billing, interface to fixed network, etc; the Base Stations, which take care of the radio frequency interface between network and mobile terminals; and the mobile terminals which are used by the users to make phone calls or data transmissions. The energy of cellular networks is mainly consumed by the base stations, rather than the core network, as the number of base stations is relatively high and their energy consumption is also quite high. In the case of UMTS, BSs altogether contribute between 60 to 80% energy consumption of the overall network [8], and only around 22% of this is due to the transceiver energy consumption [7]. Even more, the number of users in cellular networks is increasing every day and demand higher transmission rates and better performances. The industry is shifting to the next generation mobile networks (e.g. LTE) which results in the deployment of additional base stations, and therefore leads to higher energy consumption. Therefore, one of the main issues of energy saving in cellular networks is to reduce the number of base stations operating in the network. One approach is to reduce the number of deployed base stations with energy efficient network planning. Another approach, which is the one followed in this work, is to dynamically turn off some of the base stations when the network traffic is low.

When turning off base stations, there are coverage issues that have to be solved. Recently there has been a lot of work on relay technology and its applications in cellular networks. A relay is a node that receives information from the source and forwards it to the destination, so it can assist in a transmission to improve performance. Although the idea of a relay appeared in the late 60's, it hasn't been until recently, when a lot of results appeared related to cooperative communications, that they are being thoroughly researched. Relays can have many applications, like capacity enhancement, load balancing or coverage extension of cells, which is what we are interested in.

2.1.- INTRODUCTION TO CELLULAR NETWORKS

Cellular networks are radio networks made up of a number of non-overlapping cells, each served by at least one base station, that cover a wide geographic area. Several frequencies are assigned to each cell, which can be reused in other cells. Several multiple access techniques (or spectral sharing) can be used to distinguish signals from different devices, which is done by dividing the signaling dimensions along the time, frequency, and/or code space axes. In frequency-division multiple access (FDMA) the total system bandwidth is divided into orthogonal frequency channels. In time-division multiple access (TDMA) time is divided orthogonally and each channel occupies the entire frequency band over its assigned timeslot. Code-division multiple access (CDMA) is typically implemented using direct-sequence or frequency-hopping spread spectrum with either orthogonal or non-orthogonal codes. In direct-sequence each user modulates its data sequence by a different chip sequence which is much faster than the data sequence. In the frequency domain, the narrowband data signal is convolved with the wideband chip signal, resulting in a signal with a much wider bandwidth than the original data signal. In frequency-hopping the carrier frequency used to modulate the narrowband data signal is varied by a chip sequence which may be faster or slower than the data sequence. This results in a modulated signal that hops over different carrier frequencies. Typically spread spectrum signals are superimposed onto each other within the same signal bandwidth. A spread spectrum receiver separates out each of the distinct signals by separately decoding each spreading sequence.

The multiple access technique determines the re-use factor, this is, the rate at which the same frequency can be used in the network. In FDMA, for example, adjacent cells cannot use the same frequency as this would cause co-channel interference. On the contrary, with CDMA the re-use factor can be as low as 1, this is, adjacent cells can have the same frequencies so the whole bandwidth is available at each cell.

Cellular networks appeared in the 1960's and used analog communications. Second generation systems moved from analog to digital due to its many advantages. The components are cheaper, faster, smaller, and require less power. Voice quality is improved due to error correction coding. Digital systems also have higher capacity than analog systems since they can use more spectrally-efficient digital modulation and more efficient techniques to share the cellular spectrum. They can also take advantage of advanced compression techniques and voice activity factors. In addition, encryption techniques can be used to secure digital signals against eavesdropping. Digital systems can also offer data services in addition to voice, including short messaging, e-mail, Internet access, multimedia capabilities,etc.

Presently, GSM/EDGE (2G) and UMTS/HSxPA (3G) network technologies account for over 85% of all mobile subscribers. GSM uses TDMA (Time Division Multiple Access) with, typically, a frequency reuse factor of 4. UMTS uses W-CDMA (Wideband CDMA) instead, with a frequency reuse factor of 1. The next generation cellular networks will be based on LTE (Long Term Evolution) technology, which uses OFDMA (Orthogonal Frequency Division Multiple Access) for the downlink and SC-FDMA (Single Carrier FDMA, a

pre-coded version of OFDM to avoid high peak-to-average ratios (PAPR) in the user terminals) for the uplink, which also allow a frequency reuse factor of 1, although it will use a fractional reuse factor, this is, users near the base station reuse the same frequencies (or subcarriers) whereas users at the cell border are allocated to other subcarriers in a coordinated way between the base stations to minimize the interference. Other important features of future LTE networks are the following:

- The spectrum used will be flexible: 12 subcarriers per slot form a resource block of 180 kHz. The minimum spectrum used consists of a carrier with a bandwidth of 1.4 MHz containing 6 resource blocks, while the maximum consists of a carrier with a bandwidth of 20 MHz containing 100 resource blocks; as opposed to the fixed 5 MHz carrier used for W-CDMA in 3G networks.
- The system will be able to cope with at least 200 active users in every 5 MHz cell.
- It will support cells from 5 km to 100 km in the 900 MHz for rural areas; and cells of 1 km or less in urban areas with higher frequency bands (around 2500 MHz) to support high speed mobile broadband.
- It will support both FDD and TDD mode.

One of the aims of LTE is to minimize the cost and power consumption while ensuring compatibility with, and a cost effective migration from, the existing UMTS systems. The spectral efficiency in the LTE will be 2 to 4 times that of the Release 6 of HSxPA. The China Telecom/China Unicom has chosen LTE as their 4G network technology.

2.1.1.- SYSTEM ARCHITECTURE

Cellular networks mainly consist of two parts: the radio access network or base station subsystem (BSS) and the core network, which are connected through a backhaul connection. The base station subsystem is responsible for handling traffic and signaling between the core network and the user. It consists of a network of base station transceivers (called nodes B in 3G and LTE) grouped under several base station controllers (BSC or Radio Network Controllers (RNC) in 3G and LTE) which are connected to the core network. A single BSC/RNC can have tens or even hundreds of BTSs under its control. The BSC/RNC handles allocation of radio channels, is in charge of admission control, receives measurements from the mobile phones, controls handovers from BTS to BTS, etc. The BSC can route voice calls through the public switched telephone network (PSTN) or provide Internet access. It also acts as a concentrator of low capacity connections to and from the BTS into a high capacity connection to and from the core network. The Base Station is in charge of the radio interface: scrambling, modulation, scheduling, adaptive coding, link quality measurements, soft handovers, etc.
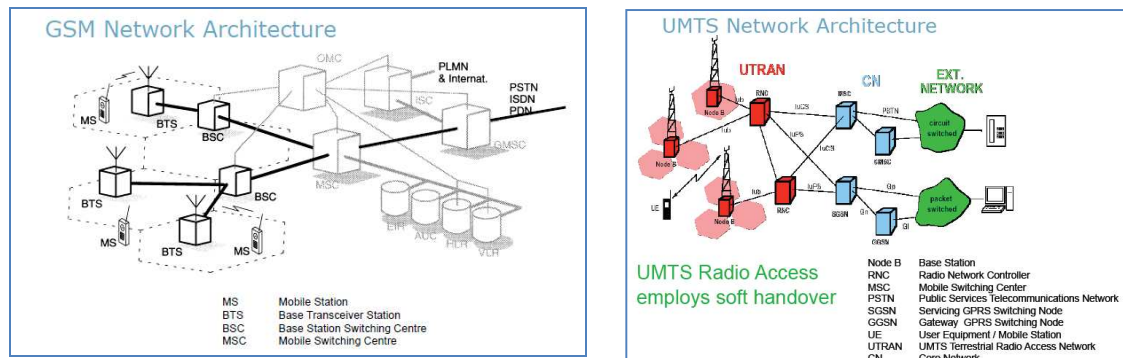
Fig. 1 - GSM & UMTS NETWORK ARCHITECTURES

The core network is in charge of routing and forwarding the user data, handovers between different technologies, it manages the databases with the user and terminals information, security issues, etc. The core network in cellular networks has suffered several changes over the last decade. For example, in the GSM second generation networks a new packet commuting network was added later to give support to GPRS technology which included gateways to external IP networks. Later on, with third generation networks like UMTS and its several releases, the core network was expanded to support soft switching (release 4) or multimedia transmissions (release 5 with the multimedia subsystem). Presently, the core network is evolving to an all-IP network in future generation networks.

2.1.2.- COVERAGE AND CAPACITY

The coverage area of a cell is the expected percentage of the cell's area where the received power is greater than a certain minimum, given that the user terminals require a minimum received SNR for acceptable performance. The Base Station transmits with a certain power so that the average received power at the border of the cell is above the minimum required bearing in mind the effects of path loss and shadowing, this is, the variation of the received signal due to the user movement and the environment where the signal is propagating. Path loss is caused by dissipation of the radiated power and the conditions of the propagation channel. Distance between receiver and transmitter and the frequency used for the communication are the main factors in path loss. The higher the frequency is, the higher the path loss and attenuation are. Shadowing is caused by obstacles between the transmitter and the receiver which cause reflection, scattering, absorption and diffraction of the signal and, therefore, causes its attenuation. Shadowing will cause some users within the cell to receive power below the average received power at the cell boundary and some users to receive power above the average. Assuming path loss and average shadowing, the coverage area is given by a circle around the base station.

Capacity refers to the theoretical maximum transmission rate that can be achieved over a wireless channel. In a single-user Gaussian channel, Claude Shannon defined capacity using the mathematical theory of information theory based on the notion of mutual information between the input and output of the channel.

In CDMA cellular networks with single-user detectors the coverage of the cell is limited by the interference caused by users in the same cell; this is, for a certain transmit power, the coverage of the cell is inversely proportional to the number of users in it. An increase in the number of active users in the cell causes the total interference seen at the receiver to increase. This causes an increase in the required received power for each user, due to the fact that each user has to maintain a certain SINR at the receiver for acceptable performance. The increase in the required received power results in the decrease of the coverage. As more users arrive to the cell, the coverage area decreases. Therefore there is a tradeoff between the coverage and the capacity in a cell. Higher frequencies are a disadvantage when it comes to coverage, but are an advantage when it comes to capacity. Pico cells become possible, and the same frequency can be used for cells which are practically neighbors. Presently, the amount of free spectrum is decreasing, and future networks will have to use the available bands at higher frequencies, meaning a decrease in coverage and an increase in base station density. Moreover, next generation cellular networks are expected to support different types of services including web browsing, FTP, video streaming, VoIP, online gaming, real time video, etc., therefore require even higher transmission rates. Physical layer technologies such as OFDM, smart antennas and Multiple Input Multiple Ouput (MIMO) systems are being designed to achieve this goal. Relay technology can be used both to increase capacity and coverage, as many papers have proved thus far.

2.2.-RELAY NETWORKS

MIMO systems have many advantages thanks to the transmit diversity it can achieve, but they are not always practical given that some devices cannot support multiple antennas because of cost, size, etc. To overcome this challenge cooperative communication techniques can be used. The main idea behind cooperative communications is that single-antenna devices can "share" their antennas to create a virtual MIMO system. The main advantage of MIMO systems is the ability to transmit different independent versions of a same signal, which are used to diminish the effects of fading. One way to achieve this diversity is to transmit the signal from different locations, thus creating spatial diversity. To do so, relays can be a useful tool.
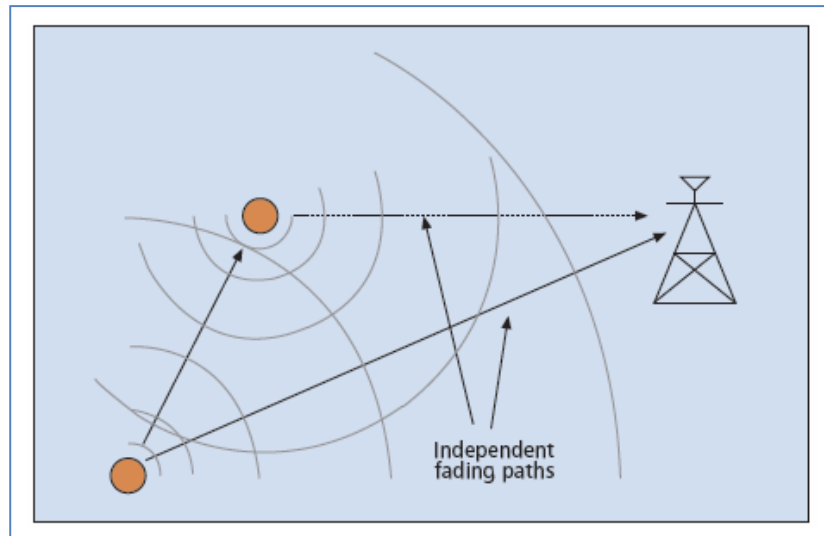
Fig. 2 - COOPERATIVE COMMUNICATION

The notion of relay channel appeared in the late 60's. E. C. van der Meulen introduced the idea of a three-terminal communication channel consisting of a source, a destination and a relay. T. M. Cover and A. El Gamal later published a paper where they computed upper and lower bounds for the capacity of the single relay channel and give an exact expression for the Gaussian degraded case. Given the complexity of the relay channel, it hasn't been until the exhaustive research on MIMO channels over the last decade that relay networks have been on the spot again, and recently there have been many publications on the topic. These focus on various issues regarding relays: forwarding strategies, deployments, applications, etc.

The primary advantage of deploying relay stations in terms of the cost is expected to come from the differences in the cost of the backhaul. When a relay station is deployed, instead of a Base Station with a wired backhaul connection, there are no direct backhaul costs. There is no cost for provisioning the wired connection, and there are no monthly charges for the backhaul. Similarly, when a relay station is deployed, instead of a Base Station with wireless backhaul, the use of a relay station eliminates the need to purchase, set up, and maintain microwave link equipment, and to purchase the rights to additional spectrum in which this equipment operates. Relay Stations are also expected to be less costly to deploy because they do not require line of sight channel conditions on the relay link, allowing greater flexibility in site selection than for a Base Stations with wireless backhaul.

The idea behind a relay channel is to use the relay to create spatial diversity sending the same signal through independent fading paths. This can be done in two steps. Firstly, the source broadcasts the signal both to the relay and the destination. In the second step, the relay transmits the received signal to the destination, so the destination ends up with two different independent versions of the same signal. The way in which the relay processes and retransmits the received signal to the destination has given rise to several strategies which have been deeply analyzed in the literature.

2.2.1.- RELAYING STRATEGIES

Although many strategies have been proposed in the literature, the three most significant ones are the following:

- AMPLIFY AND FORWARD (AF):- in this case, the relay simply amplifies the noisy version of the signal it has received in the first step and retransmits this noisy version. The destination then combines both signals to decide the transmitted bit. More generally, AF refers to any strategy where the relay linearly transforms the received signal. Although noise is also amplified in the relay, this strategy produces two independent versions of the same signal at the destination which allow for a better detection of the information sent. It has been proved that this strategy is optimal at high SNR, achieving diversity of order two.

- DECODE AND FORWARD (DF):- in DF strategies, the relay tries to detect the received information, re-encodes and retransmits the signal after detection. If detection is unsuccessful the relaying can be harmful when detecting at the destination, therefore the strategy should be implemented such that the relay only retransmits the information when detection is successful. DF requires more complex devices than AF methods, but the noise at the receiver is much lower.

- COMPRESS AND FORWARD (CF):- in this case, the relay performs a non-linear transformation on the received signal and then retransmits to destination. In this way, the relay station can compress the received signal and forward it to destination without the need to decode it. Some typical examples of CF strategies are "Estimate and Forward" or "Quantize and Forward".

2.2.2.- APPLICATIONS

Relays can have many applications in cellular networks, but most of the literature focuses on three aspects: coverage extension, capacity enhancement and load balancing. The future cellular networks (like LTE-Advanced) have very challenging requirements for transmission rates and, presently, there is a growing demand in cellular networks for coverage and capacity. Relay stations are one of the technologies being designed to meet these requirements. They have low power consumption due to their small size and have a wireless backhaul, which enables deployment flexibility and is much cheaper than a fixed backhaul. Furthermore, the installation of Relays is cheaper and faster than deploying new base stations.

Coverage extension refers to the use of relays to extend the coverage area of a given base station. This can be useful in future generation networks to avoid the deployment of excessive base stations, to extend the coverage where the direct link between the base station and the user terminal is not good enough. For example at the border of the cell or in the shadows of large objects such as tall

buildings, within the buildings themselves, or underground, etc. Capacity enhancement can be achieved by relays thanks to the spatial diversity they provide, especially when the link between the user and the relay is much better than the link between the user and the base station. Load balancing refers to the transfer of some of the traffic of one cell to a neighboring cell. This is useful when we have congested cells, this is, when traffic generated by the users is higher than the capacity of the cell. In this case, some of the traffic can be balanced to another cell that is not congested. Relay stations can be used to carry out such balancing.
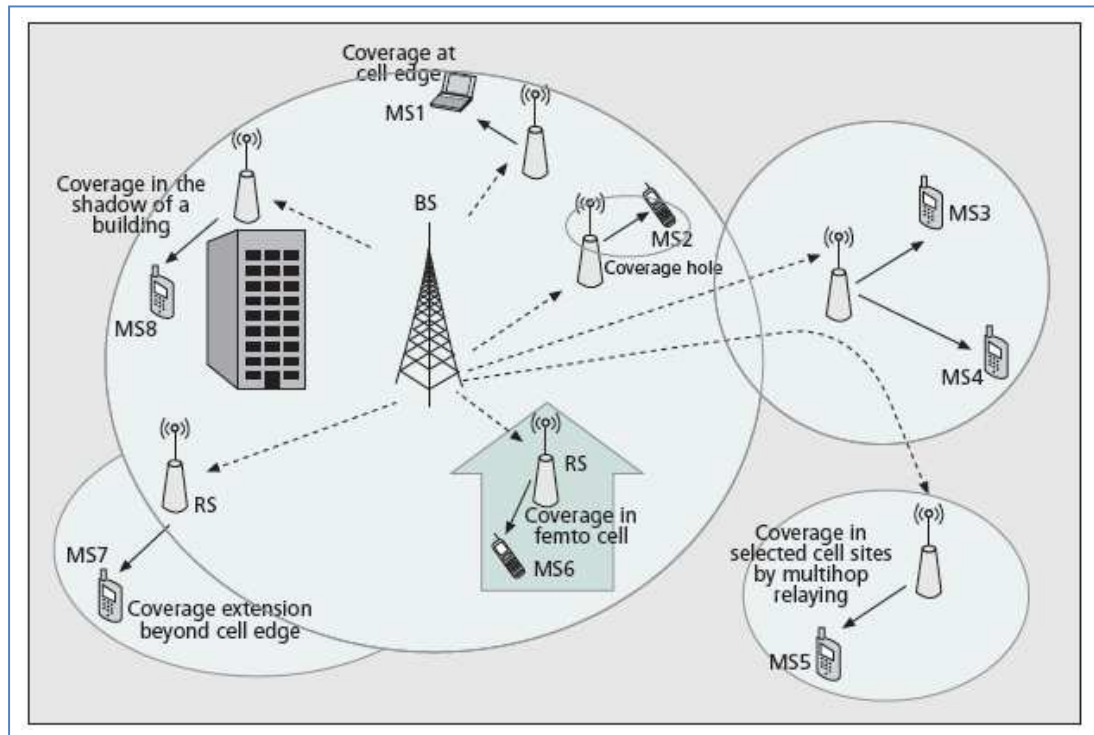
Fig. 3 - EXAMPLE RS DEPLOYMENT SCENARIOS

This topic has been exhaustively treated in the literature, for example in [14], [15], [16], [17], [18] and [19]. In [14], they consider a Gaussian relay channel and focus on maximizing coverage for a given rate. The relay location with respect to the source is a design parameter of the system model, and they evaluate DF and CF strategies, concluding that for a given placement of the relay one of the 2 strategies is uniformly optimal. In [15] they present results for different simulation scenarios and show that relay stations can provide an improvement in CINR coverage and spectral efficiency, downlink and uplink cell throughput enhancement and reduce MS transmit power. In [16] results for the coverage extension and capacity enhancement of relay stations in a realistic scenario are presented. In [17] they introduce the concept of coverage angle and coverage range to establish the relation between the coverage extension achieved and the number of relay stations, and their simulations show that the coverage range extension for MIMO relaying systems is significant as compared to direct transmission. In [18] they present an analysis of coverage extension with mobile relays and in [19] they propose dynamic load balancing schemes based on the integrated cellular and ad hoc relaying systems (iCAR), where the ad-hoc relaying stations help relay traffic from one cell to another.

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2.2.3.- MULTI-HOP CELLULAR NETWORKS

Cellular networks are based on a single-hop architecture. Service providers must construct an infrastructure with many base stations to cover the area of interest. By doing so, mobile stations can access the infrastructure in a single hop. In a densely populated metropolitan area, to support more connections, the area that a single base can cover is shrunk and the number of base stations increases. This leads to higher costs of deployment and a limited total throughput by the number of cells in the area. In the last few years another kind of wireless networks have appeared which can help to avoid the deployment of great numbers of base stations: ad-hoc networks. In ad-hoc networks, mobile stations can forward data from other stations to reach the destination in multiple hops. In this kind of networks no infrastructure or wired backbone is required. Their main advantage is that they are much cheaper to deploy, but cannot be used at very large scales, so their applications are limited (for example, in rescue operations or traveling groups). Currently, it is very difficult to use ad-hoc networks to guarantee uninterrupted high bandwidth connectivity to a large number of users but a lot of research is ongoing on this topic given its potential applications.

Multi-hop Cellular Networks (MCN) combine the ideas behind ad-hoc networks and the scale of single-hop cellular networks. The architecture of MCN resembles that of conventional cellular networks except that bases and mobile stations are not always mutually reachable in a single-hop. In MCNs, mobile stations are allowed to communicate without the involvement of the Base Station. The mobile stations can also be used to forward packets as in ad-hoc networks. The routing in MCN is done in several hops. If the source and the destination are in the same cell, other mobile stations can be used to relay packets to the destination, which achieves multi-hop routing within a cell. If not in the same cell, packets are sent to the base station first, probably in multiple hops, and then be forwarded to the base of the cell where the destination node is. Packets can then be forwarded to the destination, probably in multiple hops again, within the latter cell.

Therefore, MCNs provide a method to increase the spatial reuse of the channel by decreasing the transmitting power of mobile stations without having to pay the penalty for a large number of Base Stations. The advantages of MCNs over Single-hop Cellular Networks include more frequency reuse, higher tolerance to BS failures and higher scalability than ad-hoc networks. MCNs can provide service in dead spots in a cell, which are not reachable by the Base Station in a single hop. They also can handle hot spots better.

Existing architectures and protocols proposed for MCNs are very diverse and different in several aspects. There can be relay stations preinstalled by network operators or simply be other idle user terminals which are not transmitting their own data; radio resources at different hops may be allocated in time-division duplex (TDD) or frequency-division duplex (FDD) mode; frequency bands other than the cellular frequency band may be used for relaying; etc.

2.2.4.- OTHER ASPECTS ON RELAY TECHNOLOGY

In the previous sections we have presented relay technology and its many possible applications in present cellular networks, as well as the potential gains they can provide. But there also many complicated issues related to the practical implementation of relay technology. What are the desirable characteristics of a relay? How many relays should be deployed? Where should they be located? In what case is better for a user to use the relay? And so on. All these issues are being thoroughly researched and new results appear every month.

- RELAY CHARACTERISTICS: In most practical applications, relays are half-duplex terminals, this is, they receive and transmit signals at different times or on different frequency bands. Full-duplex relays, capable of transmitting and receiving on the same time/frequency channel, also exist. Lots of theoretical works introduce full-duplex relays to characterize capacity bounds. Furthermore, intuition suggests that they better exploit the system degrees of freedom. However, the interference-cancellation techniques they imply are computationally expensive, extremely sensitive to errors and, thus, less suitable for practical systems.

- RELAY DEPLOYMENT: A network operator always desires the most cost-effective solution with the minimal deployment expenditure to provide a satisfactory service. The optimal relay topology is still an open problem, more relays imply better coverage and capacity but introduces more interference and it is costly. The location of these relays station is also another open problem. Relay stations at the cell edges are better for coverage extension and relays between the base station and the cell edge are better for capacity enhancement, so there is a tradeoff between the distance to the base station and the application we are most interested in.

- MOBILITY: Relay stations can be fixed, nomadic or mobile. Fixed RSs are mounted in a fixed location and are not moved, so they have access to a power source. Nomadic RSs are portable. They can be moved to a location, positioned for operation and turned on. In this case, RS can have access to a power source such as a power grid or power provided by a generator, but in some cases battery operated nomadic RSs can be used. Mobile RSs operate while they are in motion. Generally, mobile RSs do not move along a predetermined trajectory, but in some cases, like when a mobile RS is mounted on a train, the RS moves along a known trajectory. When mounted on a bus or ferry, the mobile RS follows a constrained trajectory, but one that is not always precisely the same. In this case, RSs can have access to a power source such as a generator mounted on the vehicle on which the RS is deployed. In other environments mobile RSs can be battery operated.

- RELAY SELECTION: once the relays are deployed, the problem of how to select the optimal relay for a transmission, or if more than one relay for cooperation should be selected. In a scenario with N relays, there are $2^N - 1$ selection options. Many single relay and multiple relay selection schemes can be found in the literature. Some single-relay selection examples include Best Relays Selection (the relay whose path has the maximum SNR is selected), Nearest Neighbor Selection (the relay that is the nearest to the source is selected), Best Worse Channel Selection (in which the relay whose worse channel (the one from the source or the one to the destination) is the best is selected), and Best Harmonic Mean Selection (in which the relay with the largest harmonic mean of the two channels is selected). The

multiple relay selection schemes are, normally, a generalization of the single relay selection schemes.

Many other issues like the overall interference in the network, handling handovers, fairness of the system, and transmit and receive requirement on the mobiles are also an open problem still.

2.3.-ENERGY SAVING IN CELLULAR NETWORKS

As has been stated in the motivation for this project, energy saving has become an important issue in cellular networks given its increasing power consumption and the increasing social concern on environmental issues. The great number of base stations deployed in a cellular network make them the main power consumer. Some reports say that about 60 to 80% of the energy consumed by a cellular network is due to the radio access subsystem.

2.3.1.- STATIONS POWER CONSUMPTION

The power consumption in a Base Station is mainly due to the power unit, the cooling system and switch and controller that connect the base station to the backhaul. The power consumption for the transmissions is due to the power amplifier, combiners and duplexor, converters, etc. and is responsible for approximately the 20% of the total energy consumption of the base station.

Instead, relay stations have low power consumption due to their small size and that they have a wireless backhaul, which enables deployment flexibility and is much cheaper than a fixed backhaul. Furthermore, the installation of relays is cheaper and faster than deploying new base stations. Thanks to the compact physical characteristics and low power consumption, relay stations can be mounted on structures like lamp posts with power supply facilities, without the need of a new installation.

2.3.2.- ENERGY SAVING SCHEMES

As said before, currently there is an increasing demand for higher data rates. Because of this, cell sizes are shrinking and more and more base stations need to be deployed, incrementing the costs. By improving the energy efficiency of base stations in cellular networks a great saving can be obtained in both environmental and cost point of view. There are many energy saving schemes can be applied which deal with improved transmitter efficiency, system features, fresh air cooling, alternative energy sources or energy saving during low traffic. Most of them can be classified in the following three categories:

- MINIMIZING BASE STATIONS' ENERGY CONSUMPTION: to minimize the base stations' energy consumption the energy efficiency has to be improved, especially of the power amplifier in the transmitter chain. The power amplifier depends on the working frequency band, the modulation used and the environment where the transmission takes place. In the last years, the energy efficiency of the transmissions has been improved with the implementation of more efficient modulations and coding. Another way to minimize the energy consumption of the base stations is to shut them off completely or parts of it during low traffic, which is the approach taken in the present work. The site can also be improved

to save more energy, for example, using air cooling instead of air conditioner as much as possible, reduce the length of the feeder cable to decrease its losses by changing the disposition of the elements in the site, etc.

- MINIMIZING THE NUMBER OF BASE STATION SITES: there is a tradeoff between the size of the cells (this is, the number of base stations) and the energy they consume. Larger cells generally consume more power. Several features, like using low frequency bands, smart antennas, cooperative transmissions or sectorization, can be used to optimize the balance between the cell size and the capacity in order to minimize the number or sites. The network design plays an important role in achieving this.

- USE OF RENEWABLE SOURCES: renewable sources, especially solar or wind power or a combination of both, can be use to power a site. It is necessary to bear in mind the location of the site and the energy requirements of the site for its design. They can be useful especially in sites where the availability of electrical grid is limited and to decrease the CO_2 emissions.

3.1.- RELATED WORK

Although there is a lot of literature on the topic of energy saving in cellular networks, before presenting the proposed algorithm proposed in this work, we introduce two papers related to the present work.

3.1.1.- TRAFFIC MODEL

In [20] they characterize the amount of energy that can be saved by reducing the number of active cells during the periods when they are not necessary because the traffic is low. When some cells are turned off, the coverage and service provisioning is taken care of by the remaining active cells to guarantee the service is available over the whole area.

As already mentioned, the radio access system of the cellular network is responsible for a lot of the power consumed by the network, mainly because the number of base stations in a network is considerably higher than the number of the other elements. Therefore, if some form of energy saving is achieved in the base stations, it is multiplied by a large factor, achieving a considerable energy saving in the whole network. In this paper they propose switching off base stations when traffic is low, this is, reducing the number of active cells in low traffic periods, given that the remaining active cells are able to cope with their own traffic as well as the switched-off cells' traffic. Traffic fluctuations can be the result of different situations: the day-night behavior of users, the movement of users from residential zones during the night to office districts during the day and back, etc.
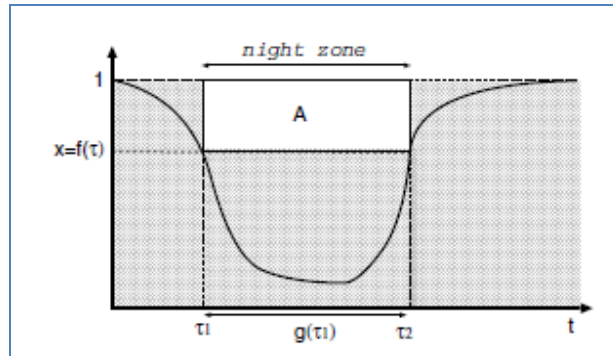

Fig. 4 - EXAMPLE OF DAILY TRAFFIC PATTERN AND ENERGY SAVED (GIVEN BY AREA A) BY SWITCHING OFF CELLS

Presently, network planning is carried out to satisfy the peak demands in the area, making the system overdimensioned during some periods of time when the traffic is low. In the paper they assume that if the peak traffic periods can be served by K cells, each with traffic f, then when the traffic decreases to a fraction of f, xfK ($x<1$) just xK cells are necessary to satisfy the performance requirements. Therefore, *(1-x)K* cells can be turned off and *(1-x)%* of the energy can be saved with respect to the peak traffic period energy consumption. They assume the switching scheme is fix, this is, either a large

number of cells is turned off during a small period of time or else a small number of cells are turned off during a larger period of time, and optimize the fraction of cells to turn off to achieve the maximum energy saving.

For their analysis they consider a function f(t) for the daily traffic pattern in a cell normalized to peak hour traffic. They assume the traffic pattern identical in all cells in the considered area. In this case, when a fraction $x<1$ of the cells are switched off the remaining active cells have to sustain a traffic demand given by $\frac{1}{x}f(t)$, which has to be <1 to satisfy the performance requirements. To optimize the energy saving they consider both symmetric traffic patterns and asymmetric patterns and yield equations to compute the instant when the switching scheme should be performed and the number of cells to be turned off. As an example, they compute the values for a trapezoidal traffic pattern with different slopes and conclude that the energy saving achieved is of at least 25% with respect to an all-cells-active scheme. Finally, they consider several real network topologies and compute the fraction of cells that can be turned off in each case for a real traffic profile.

In conclusion, they prove that significant energy saving can be achieved in the access system of a cellular network by turning off some cells during low traffic periods of time. They are assuming traffic is uniform across cells and that the coverage can be filled by the remaining active cells when a cell is switched off. Both assumptions will be addressed later on.

3.1.2.- DYNAMIC ENERGY SAVING

[21] also tackles with switching off base stations in low traffic and the tradeoff between energy saving and coverage guarantee. They relate to previous load balancing studies, which are centered in high traffic situations, given its dynamic nature for resource control.

The aim is to minimize the average energy consumption of the Base Stations while satisfying the traffic requirements from users. They formulate an optimization problem where the function to minimize is the energy consumption of the active base stations while satisfying two constraints: each user is served by only one base station and the bandwidth occupancy of the users associated to a base station cannot exceed its maximum available bandwidth, this is, its available resources. They assume the intercell interference is already taken care of. Given that the problem is very hard to solve they propose a centralized and a decentralized algorithm to carry out the optimization.

In the centralized algorithm, at every iteration, the base station that still hasn't been assigned that can give service to the maximum number of users (the one that would have the most resources occupied) is turned on. When all users are already served by a base station or all base stations are on the algorithm terminates. If all base stations are on and there are still users not associated to any base station, these users are in outage. They also introduce a protection margin to reduce the outage during the periods between when the algorithm is run. The decentralized algorithm doesn't require that all the channel information and traffic requirements are known at the network side. In this case, the user selects the serving base station according to the maximization of a utility function.
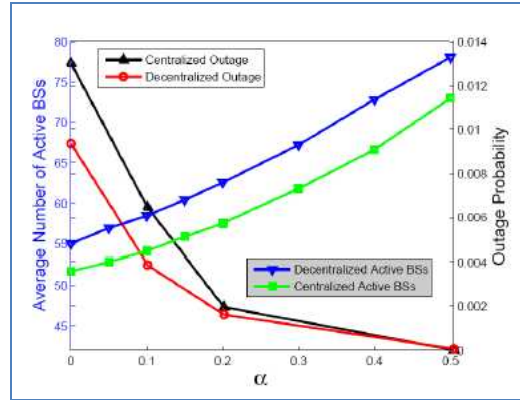
Fig. 5 - NUMBER OF BASE STATIONS TURNED OFF VS. OUTAGE PROBABILITY FOR DIFFERENT PROTECTION MARGINS

Finally, they run some simulations and compute the tradeoff between the number of base stations that can be turned off, this is, the energy saving achieved, and the outage probability of the system.

3.2.- ALGORITHM

In the following section the problem formulation and implemented algorithm are presented. We consider **B** the set of base stations and **R** the set of relay stations. Each station has a fix cost, related to power supply, air conditioning at the site, etc; and a variable cost which depends on the number of users associated to the base station and the quality of the channel between them.

3.2.1- PROBLEM FORMULATION

The goal is to minimize the total power consumption of all the stations while satisfying the performance requirements. The problem can be formulated as the following:

$$\min \sum_{B'(t)} \left(cf_b + \sum_{i=1}^{u(b,t)} cv_b * p_{bi}(t) \right) + \sum_{R'(t)} \left(cf_r + \sum_{i=1}^{u(r,t)} cv_r * p_{ri}(t) \right)$$

s.t.

$$\sum_{B} a_{bi}(t) + \sum_{R} a_{ri}(t) \leq 1, \qquad \forall i = 1, \ldots, N_u(t)$$

$$\sum_{i=1}^{u(b,t)} a_{bi}(t) * \frac{\rho_i(t)}{W_0 \log\left(1 + \frac{P_{t_{bi}} * L_{bi}}{N_0}\right)} \leq W_{b_{max}}, \qquad \forall b = 1, \ldots, B$$

$$\sum_{i=1}^{u(r,t)} a_{ri}(t) * \frac{\rho_i(t)}{W_0 \log\left(1 + \frac{P_{t_{ri}} * L_{ri}}{N_0}\right)} \leq W_{r_{max}}, \qquad \forall r = 1, \ldots, R$$

20

Where $a_{bi}(t) \in \{0,1\}$ and $a_{ri}(t) \in \{0,1\}$ indicate if user *i* is associated with base station *b* or relay station *r*; B'(t) and R'(t) are the base stations and relay stations which are switched on at time *t*; cf_b, cf_r, cv_b and cv_r are, respectively, the fix cost of a base station, the fix cost of a relay station, the variable cost of the base station and the variable cost of a relay station; $p_{bi}(t)$ and $p_{ri}(t)$ are the transmission power between the base/relay station and user *i*; $u(b,t)$ and $u(r,t)$ are the number of users associated to base station *b* or relay station *r* at time *t*; $N_u(t)$ are the total number of users in the system at time *t*; $\rho_i(t)$ is the rate requirement for user *i*; $W_0 \log\left(1 + \dfrac{P_{t_{ri}} * L_{ri}}{N_0}\right)$ is the spectrum efficiency is rate per unit bandwidth; $P_{t_{bi}}$ and $P_{t_{ri}}$ are the power between the base/relay station and the user; L_{ri} is the power loss of the transmission; and $W_{b_{max}}$ and $W_{r_{max}}$ are the maximum available bandwidth of the stations.

The first constraint means a user can be associated just to one base station or one relay station. The second and third constraints mean that the resources occupied by all users associated to a base station or a relay station cannot exceed the maximum number of resources available at that station. The formulated problem is very hard to solve, therefore, the following algorithm is proposed to achieve the goal.

3.2.2.- CENTRALIZED ALGORITHM

Following the idea behind [20], we propose a centralized algorithm that determines how many base stations should be turned off. We assume the maximum traffic the network can cope with is known and use it to determine the active base stations. We also assume all the channel information and traffic requirements are known.

At the beginning, given the maximum traffic the network can cope with and the total number of base stations, we compute the thresholds where there is a change of state in the system, this is, a base station should be turned off/on. For N_b base stations we compute the $N_b - 1$ thresholds by:

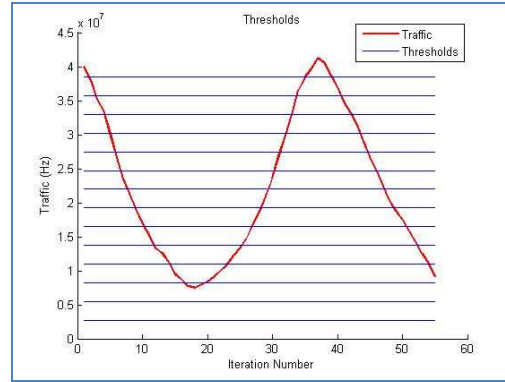$$Threshold(j) = \frac{N_b - j}{N_b} * T_{max}$$

Fig. 6 - EXAMPLE FOR 15 BASE STATIONS

Therefore, if the current traffic is equal to or less than $Threshold(j)$, j base stations can be switched off. The algorithm is the following:

Input: $Thresholds$, B, R, $N_u(t)$, P_{drop} , $u(b,t) and u(r,t)$

Output: *B', R'*

    (i)   Compute the current traffic in the system, T_{curr} ;

    (ii)   Update the current traffic considering the dropping probability in the system: $T_{curr} = T_{curr}\left(1 + P_{drop}\right)$;

    (iii)   Find *j* so that

$$Thresholds(j+1) * (1 - margin) < T_{curr} < Thresholds(j) * (1 - margin)$$

    (iv)   Switch off/on base stations accordingly (update *B'*):

        a. If *n* base stations should be turned off, turn off the ones with less traffic.

        b. If *n* base stations should be turned on, turn on the ones whose

In step 2, we include the dropping probability, P_{drop} , in the current traffic. This is because the computation of the current traffic only considers the users which are currently being served by the base stations and does not account for the users whose call has been dropped because they have been unable to find a base station or relay station with enough resources available covering its position. The

P_{drop} is computed during the time interval between successive iterations of the algorithm, this is, we only consider the dropping probability the system has endured since the last iteration of the algorithm was run.

The margin in step 3 is to reduce the dropping probability of the system. The thresholds are computed for the limit case and assuming the traffic is evenly shared by all cells, this is, if the traffic increases during the interval time between successive iterations of the algorithm, which is very probable given the randomness of traffic, most of the user's calls will be dropped. To avoid this we introduce a certain margin for the thresholds so the switching of base stations does not happen for the limit traffic and there is a certain protection margin to account for the randomness of traffic. Another possible approach to limit the dropping probability is to use a conservative T_{max} instead of the theoretical maximum.

4.- SYSTEM MODEL

In the previous section, we presented the algorithm we will use to carry out the energy saving. In this section we address the system model we will be using to test the algorithm.

4.1.- NETWORK TOPOLOGY

The network considered consists of a 10 by 10 grid of hexagon cells, each covered by a Base Station situated in the middle of the cell. To simplify the model, the frequency re-use of the system is 1, this is, all base stations and relay stations will use the same frequencies. All base stations have the same maximum available bandwidth. The relay stations associated to each base station depend on the deployment.
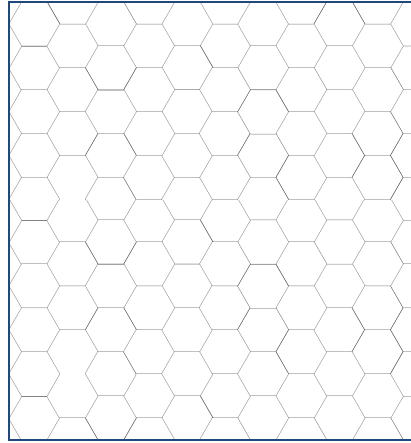
Fig. 7 - NETWORK TOPOLOGY

4.1.1.- RELAY STATION DEPLOYMENT

Up until now the relay station optimal deployment is still an open topic. Therefore we will consider 3 different deployment scenarios, as well as a no-relay scenario, to compare their performances. The relay station will be used to aid in the coverage of switched-off cells, therefore, if the base stations associated to the relay station are all on, the relay station will be turned off. Likewise, if the base stations are all off, the relay station will be also turned off since it will have no base station where to forward the user's data. The three deployments considered are:

(i)   Relay Stations at the border between two base stations: In this case, every relay station will be associated to the 2 base stations whose border the relay station belongs to. If both base stations are turned on or both base stations are turned off the relay station will be turned off. If only one of the base stations is on, the relay station will forward all its traffic to this base station.
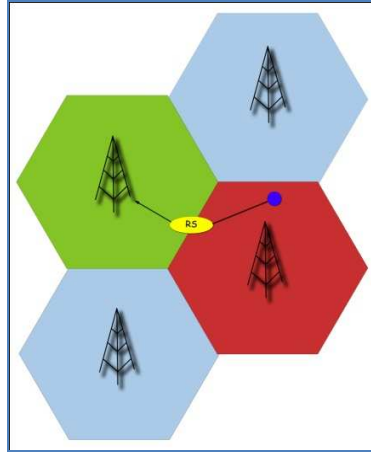
Fig. 8 - DEPLOYMENT WITH RELAY STATIONS IN THE MIDDLE

(ii)   Relay Stations in the corner: in this case, the relay stations will be in the corner between three neighboring cells. It will be associated with the three base stations whose border the relay station belongs to. If all three base stations are turned off or all three of them are turned on, the relay station will remain turned off. Otherwise, the relay station will be turned on and will forward the traffic to the active base station where it occupies fewer resources.
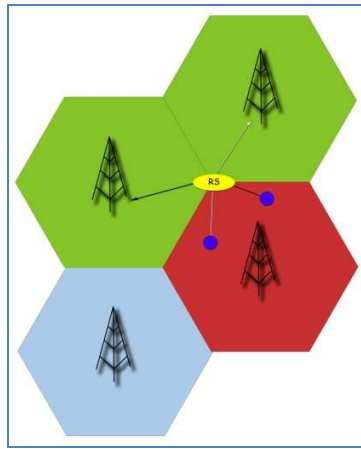

Fig. 9 - DEPLOYMENT WITH RELAY STATIONS IN THE CORNER

(iii)   Relay Stations inside the cell: in the third case, the relay stations will be inside the cell. We consider three relay stations for every cell, deployed in the center of the sub-cell obtained considering three-sector cells. It will be also associated to the three nearer base stations and the power state of the relay station will be the same as in the previous case.
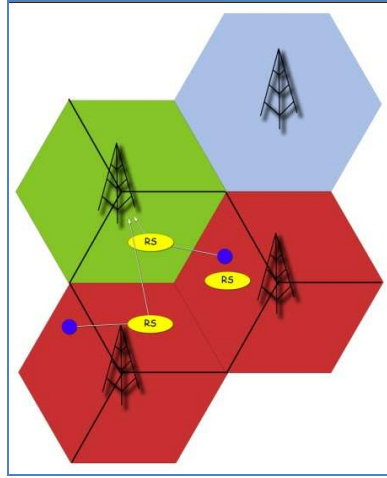
Fig. 10 - DEPLOYMENT WITH RELAY STATIONS INSIDE

4.2.- SCENARIO

As mentioned above, we consider a frequency reuse factor of 1. This can result in considerable intercell interference, as not only neighboring cells are using the same frequencies but also the relay stations are doing so. Although this is the case, to simplify the simulation we do not consider the effects of interference in our system model, as can be seen in the formulation of the previous section. We assume that the interference is taken care of by some interference management scheme. All base and relay stations will have the same available bandwidth, this is, the same number of resources to be occupied by the users.

4.2.1.- TRAFFIC MODEL

In practical scenarios, the traffic will differ depending on the environment. In urban environments there is usually heavy traffic and the system is capacity limited. In suburban or rural environments, the traffic is usually light and the system is range limited. We are considering a scenario where there is a variation from heavy traffic during some period of time to light traffic for other periods of time. The average traffic, this is, the average user arrival rate, λ, will follow a deterministic pattern that models the high-low traffic behavior, while the service time will be exponentially distributed with mean μ. λ will vary during the simulation to emulate the high-low traffic variation while μ will be fix. We will consider two high-low traffic variation patterns in the simulations. The first will be a decreasing λ pattern and the second one will have two peaks, this is, after decreasing for some time, traffic will increase again to a certain level and finally decrease to very low traffic.
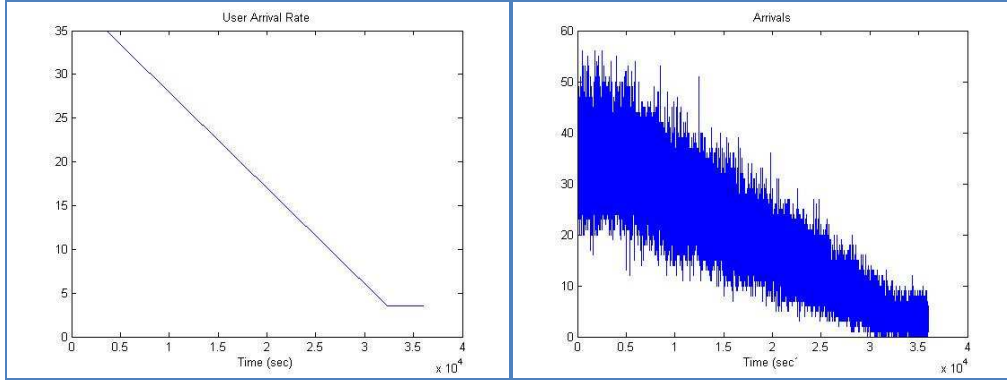
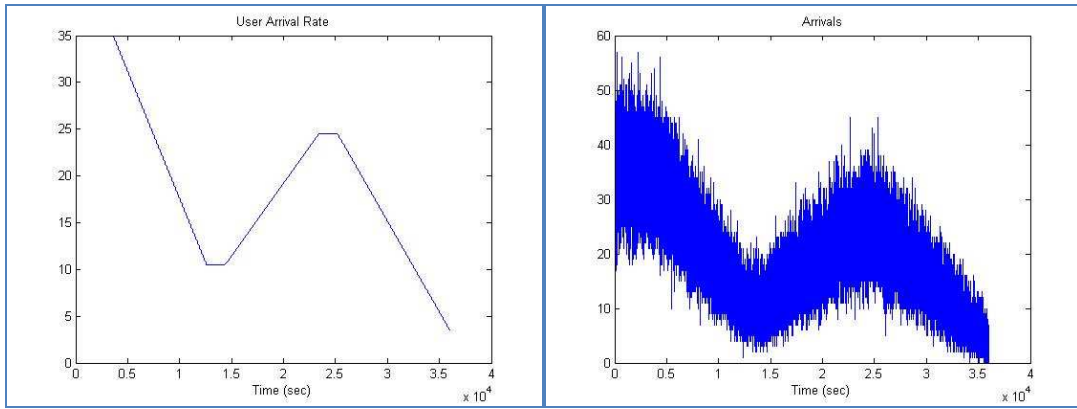**Fig. 11 - DECREASING PATTERN AND EXAMPLE OF POISSON ARRIVALS**

Fig. 12 - 2 PEAK PATTERN AND EXAMPLE OF POISSON ARRIVALS

We will consider two different traffic models to compare their performance: a spatially uniformly distributed traffic and a scenario with a hot spot. In the uniform case, users will arrive randomly at any position in the grid and will associate to the base station or relay station where it occupies fewer resources that cover its area. In the second case, there will be a hot spot in the middle of the scenario. The hot spot will be generated with a normal distribution with mean the center of the scenario and standard deviation the size of the grid. This way approximately the 25% of the traffic will concentrate in the middle cell and its 6 neighboring cells.

4.2.2.- PROPAGATION MODEL

For the propagation model, only path loss is considered. We use the simplified path-loss model defined by

$$P_r = P_t K \left[\frac{d_0}{d} \right]^\gamma$$

$$P_r(\mathbf{dBm}) = P_t(\mathbf{dBm}) + K(\mathbf{dB}) - 10\gamma \log_{10} \left[\frac{d_0}{d} \right]$$

where *K* is a constant that depends on the average channel attenuation and the antenna characteristics, d_0 is a reference distance for the antenna far field and γ is the path-loss exponent. We will use $K = 1$ and $d_0 = 1$ for simplification, given we are interested in the relation between the different deployments and not in the exact value for each case. The path loss coefficient chosen is 4 for the propagation between the user terminal and the base/relay stations and 2 for the propagation between the relay station and the base station. We choose a smaller value for the latter because fixed relays can be deployed so they have directional antennas with the base station and are in line-of-sight, therefore having better channel conditions.

4.2.3.- COVERAGE

Present cellular networks are generally interference limited and not coverage limited, this is, the number of users associated to a base station usually is not determined by the coverage area of this base station (the area where the noise of the propagation does not overwhelm the signal of the base station), but by the interference they produce on each other (the interference from other users is higher than the noise). Therefore, base stations are deployed densely and can cover areas bigger than their cell size; so, although the cell radius is *r*, we define that the base stations and relay stations in our model can cover up to a maximum distance of *2r*. Further than that, the SNR received at the user terminal is below the minimum SNR the user needs to communicate correctly.

In our scenario, as the traffic decreases, more and more base stations are turned off. Some areas of the network can therefore have no coverage while others have two or more base stations covering them. To avoid this and guarantee coverage not all base stations can be turned off, some of them are blocked so any user arriving at the system can theoretically be covered by a base or a relay station (if their resources are fully occupied, the user's call will be dropped although the station covers its area).

In the case where the traffic decreases even further and all remaining active base stations are blocked but, due to very low traffic, another base station should be turned off, the base stations are unblocked and coverage is no longer guaranteed.

4.2.4.- POWER CONSUMPTION MODEL

The power consumption of a base station or a relay station depends on a lot of factors: the size of the site, its backhaul connection, its location, etc. We will assume the ratio between the cost of a relay station and a base station is of 0.1, for this is the average ratio in a typical network deployment and can be found in [en1].

Item of Expenditure	Relay Node	Site (with 3 BS)
Hardware	10 kEUR	80 kEUR
Loan	3 years at 8 %	8 years at 8 %
Installation	5 kEUR	30 kEUR
Rental costs	100 EUR per month	1000 EUR per month
Energy costs (at 10 Cent per kWh)	438 EUR p.a. (500W)	4.4 kEUR p.a. (5kW)
Life-Span	10a	10a
Cost-Ratio	$\alpha_{RN} = C_{Relay}/C_{Site} = 0.1$	

Fig. 13 - EXAMPLE FOR INITIAL AND OPERATING COSTS FOR A RELAY NODE AND A CELL SITE

The model of the energy consumption of a station following the previous formulation consists of the sum of the fix costs and the variable costs of the station. For simplification (again, we are looking for comparison ratios and not for the actual real values), we will choose the fix cost of a base station to be of 100 units and the variable costs to vary from 0 to 20 units, given that approximately 22% of the total energy consumption is due to the transceiver. The exact value of the variable costs will depend on the number of users and the transmission power the base station is using to reach them or, equivalently, on the number of occupied resources the station has at that moment.

The simulations were carried out in Matlab. For every case, 5 simulations were averaged. The parameters of the simulation were:

- Initial λ = 35 users/second

- μ = 1/180sec

- Rate requirement for each user = 122 kbps

- Transmission power of Base Station = 43 dBm

- Transmission power of Relay Station = 33 dBm

- Available Bandwidth = 500 kHz

- Running Time = 10 hours

- Training period = 1 hour

The initial λ was chosen after running some tests to find the arrival rate the system was able to cope with for a blocking probability below 1% for the chosen bandwidth. Therefore, the maximum traffic the algorithm uses to compute the thresholds is not the theoretical maximum, but a reasonable value in practical scenarios The transmission power of the relay station is 10 dBm less than that of the base station, this is, it is 10% the transmission power of the base station. The bandwidth was chosen so the simulation time was not excessive. Since we are interested in the relation between the simulations and not the actual values, the previous choice of parameters is not significant. To compute the current traffic for the base stations in the system for the algorithm we compute the total bandwidth which is occupied at that moment. The first hour of the simulation is to stabilize the number of users and to compute the maximum traffic the system can cope with. After that, the algorithm is run every 10 minutes during the 9 hours of the simulation, so 55 iterations of the algorithm are carried out.

The results for the different simulations are presented below.

5.1.- DECREASING Λ WITH SPATIAL UNIFORMLY DISTRIBUTED TRAFFIC

The following figure represents the number of base stations that are being turned off during the simulation as the traffic decreases. As can be seen, the difference between the number of turned off base stations in the scenario with relays and the scenario without relays is significant and both converge to turning off all base stations except for one in very low traffic. Instead, there are no significant differences between the different relay deployments.
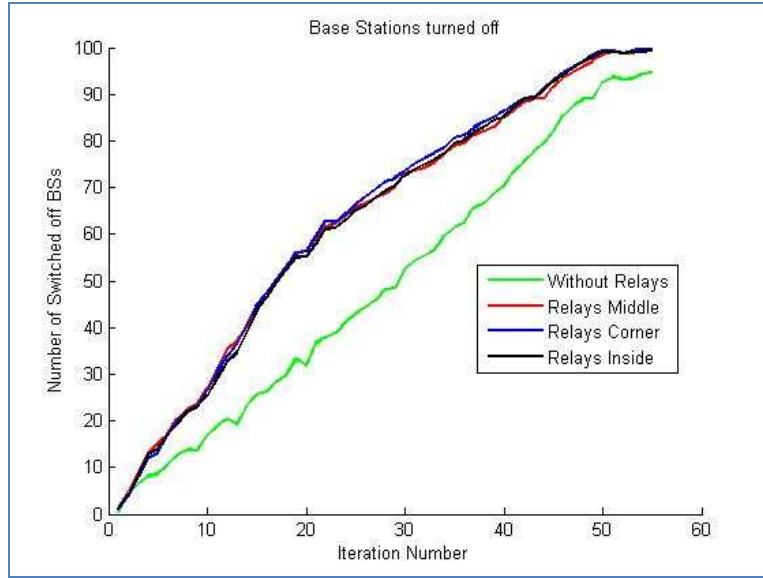
Fig. 14 - NUMBER OF BASE STATIONS TURNED OFF DURING SIMULATION

The following figure represents the energy consumption of the different scenarios during the simulation. There is a significant energy saving achieved with respect to a scenario when no energy saving scheme is used, this is, no base station is turned off.

The deployments with relays also achieve more energy saving than the scenario without relays in average, although for very low traffic and very little base stations active, the consumption of the relays is significant and the energy saving achieved with respect to no relaying is negligible. The scenario with the maximum average energy saving is the deployment with relays in the corner of the cells, while the deployment with relays inside the cells has the least energy saving of the relaying scenarios. The average energy savings are summarized in the table below.

Average Energy Saving Achieved	With respect to No Energy Saving Scheme	With Respect to No Relaying
No Relaying	43.67%	-
Relays in the Middle	48.49%	10.74%
Relays in the Corner	50.01%	14.88%
Relays Inside	45.49%	4.34%

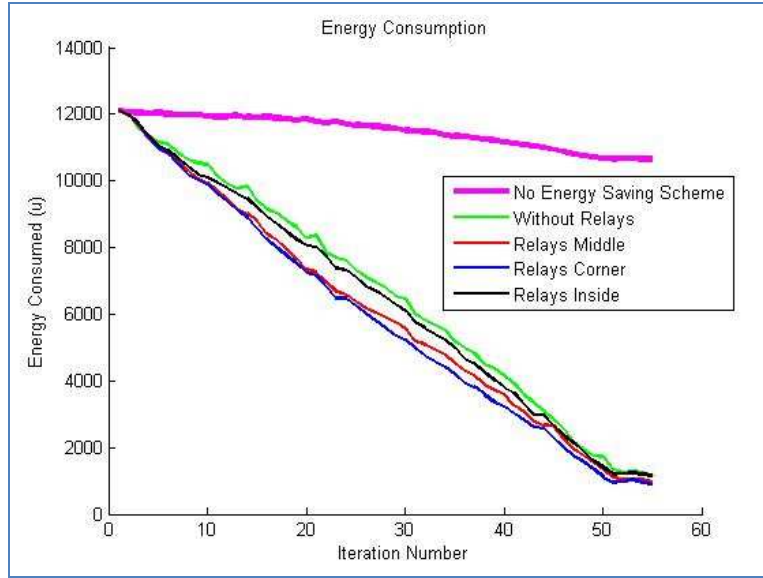**Fig. 15 - ENERGY SAVING RELATION BETWEEN DIFFERENT DEPLOYMENTS**

Fig. 16 - ENERGY CONSUMPTION DURING SIMULATION

The last figure represents the blocking probability of the scenario during the simulation. Here, the difference between the blocked base stations stage and the unblocked base stations stage can be seen. The blocking probability increases drastically when the base stations are unblocked and the coverage is no longer guaranteed. There is a delay between the non-relaying deployments and the relaying-deployments in the moment where this change of state happens. This evidences the effectiveness of relaying for coverage extension.

The deployment with the relays inside the scenario yields a better performance in terms of blocking probability but, as we have seen before, it is the deployment with the least energy saving with respect to the other relay deployments.
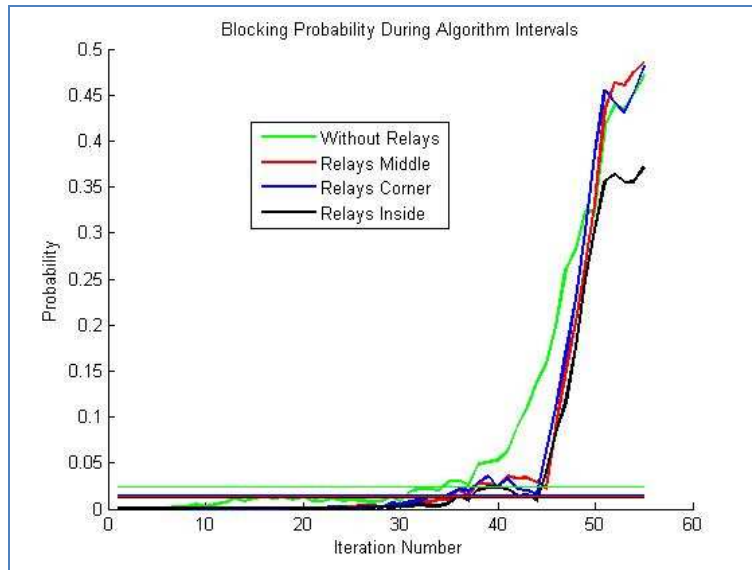
Fig. 17 - BLOCKING PROBABILITY DURING SIMULATION

5.2.- DECREASING Λ WITH A HOT SPOT

When the user arrivals are not uniformly distributed spatially but there is a hotspot in the centre of the scenario, the results are quite similar to the previous case. The difference now between the number of base stations turned off between the relaying and non-relaying deployments is a little less, but still significant.
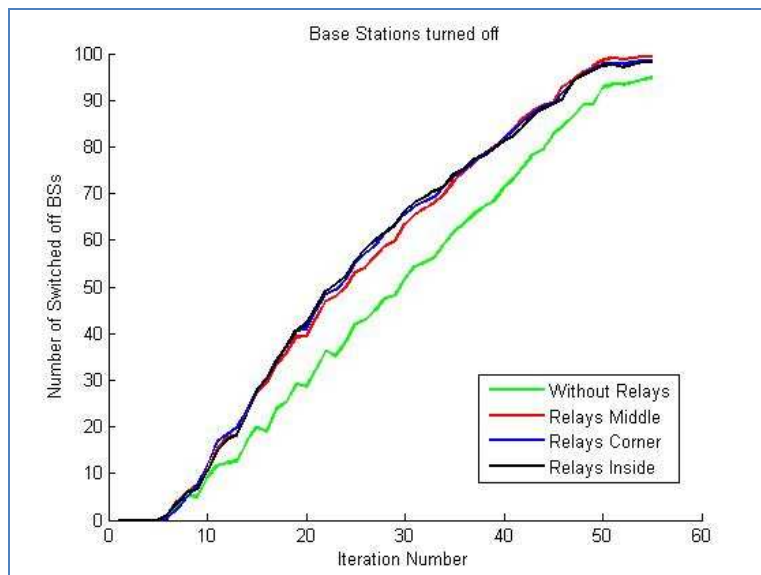

Fig. 18 - NUMBER OF BASE STATIONS TURNED OFF DURING SIMULATION

The energy saving achieved is a little less than in the previous case, and the difference between the non-relaying and relaying deployments is also less significant. Moreover, the deployment with the relays inside the cell achieves less energy saving than the non-relaying deployment, but its performance is better since its dropping probability is significantly less. Again, the deployment which achieves the most energy saving is the one with the relay stations at the corner of the cells, but the difference with the other deployments is not very significant.
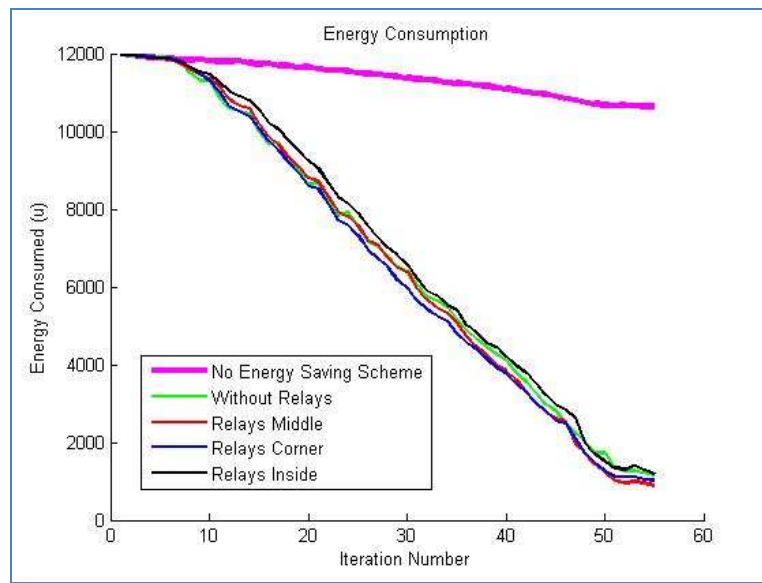

Fig. 19 - ENERGY CONSUMPTION DURING SIMULATION

Average Energy Saving Achieved	With respect to No Energy Saving Scheme	With Respect to No Relaying
No Relaying	41.29%	-
Relays in the Middle	41.95%	4.36%
Relays in the Corner	42.76%	4.91%
Relays Inside	39.13%	-4.89%

Fig. 20 - ENERGY SAVING RELATION BETWEEN DIFFERENT DEPLOYMENTS

The last figure is the blocking probability during the simulation. In this case, we can see that in the higher traffic period, the dropping probability is above 1%, so the scenario can't cope with the hot spot in this case. As the traffic decreases, the dropping probability also decreases until the moment when the base stations are unblocked and the coverage is no longer guaranteed. Similarly to the previous case, there is a delay between the start of the coverage problem between the non-relaying and the relaying scenarios. In this case, both the deployments with relays in the corners and with relays inside the cell have better performance than the other deployments.
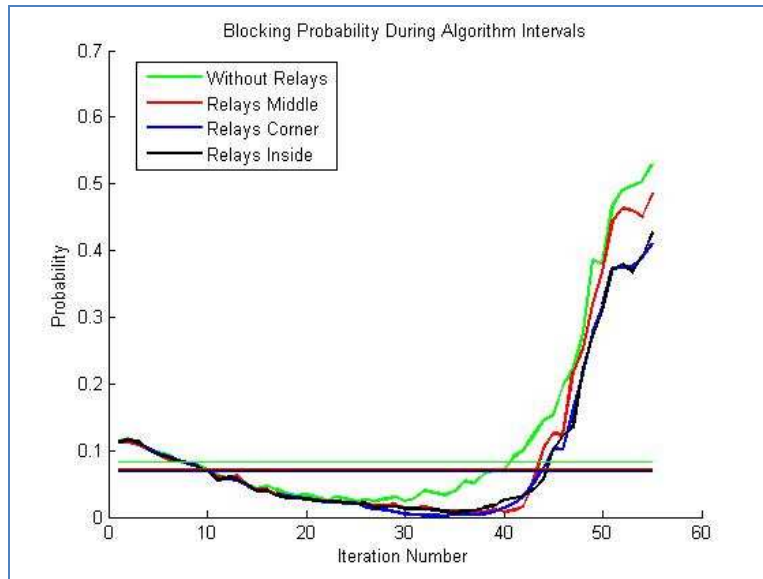
Fig. 21 - BLOCKING PROBABILITY DURING SIMULATION

5.3.- 2 PEAK PATTERN WITH SPATIAL UNIFORMLY DISTRIBUTED TRAFFIC

The traffic now follows the 2 peak pattern instead of being monotically decreasing. To simplify the simulation we have not included the deployment with relays in the middle between two cells, since its performance is a little poorer than the deployment with relays in the corner of the cells.

Again, the difference between the number of base stations switched off is significant between the relaying and non-relaying schemes. Both relaying deployments are very similar.
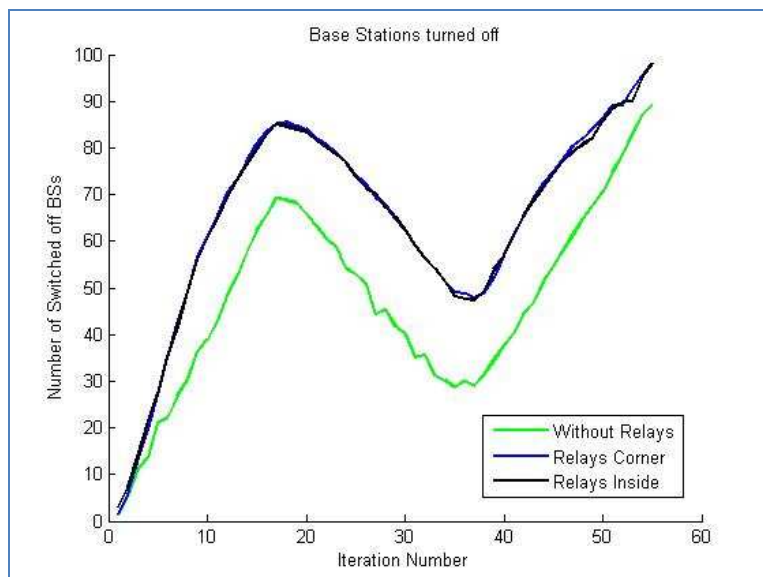

Fig. 22 - NUMBER OF BASE STATIONS TURNED OFF DURING SIMULATION

In terms of energy consumption, the deployment which achieves the most energy savings is the deployments with relays in the corner and the deployment without relaying is the scenario with the less energy saving achieved. The energy savings achieved with respect to using no energy saving scheme are very similar to the previous case, but in this case the energy savings of the relaying deployments with respect to the non-relaying deployment is a little greater.
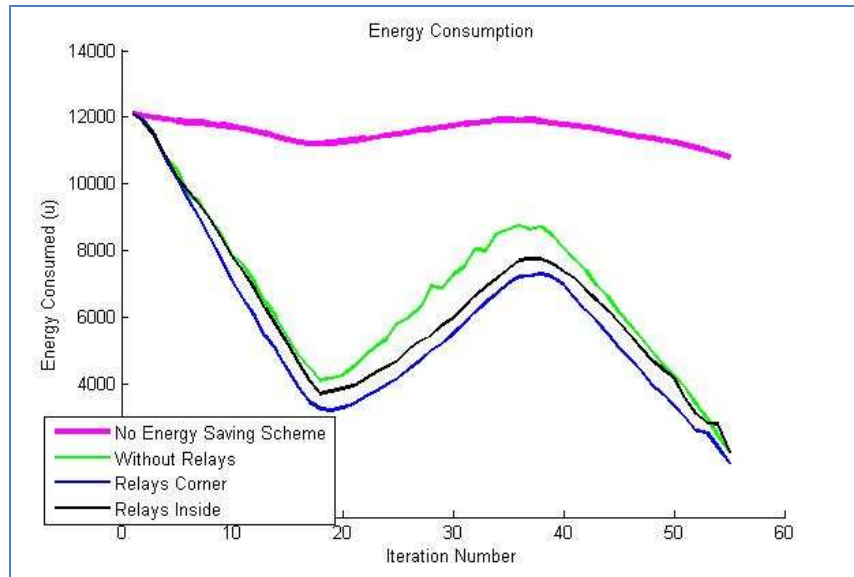

Fig. 23 - ENERGY CONSUMPTION DURING SIMULATION

Average Energy Saving Achieved	With Respect to No Energy Saving Scheme	With Respect to No Relaying
No Relaying	41.67%	-
Relays in the Corner	50.61%	17.01%
Relays Inside	45.50%	6.76%

Fig. 24 - ENERGY SAVING RELATION BETWEEN DIFFERENT DEPLOYMENTS

The last figure is the blocking probability during the simulation. In this case, the deployment with relay stations in the corner has, in average, higher blocking probability than both the other deployments, especially during the second traffic peak. There is also a delay in when the coverage is no longer guaranteed and the better performance is for the deployment with relays inside the cell, as in the previous cases.
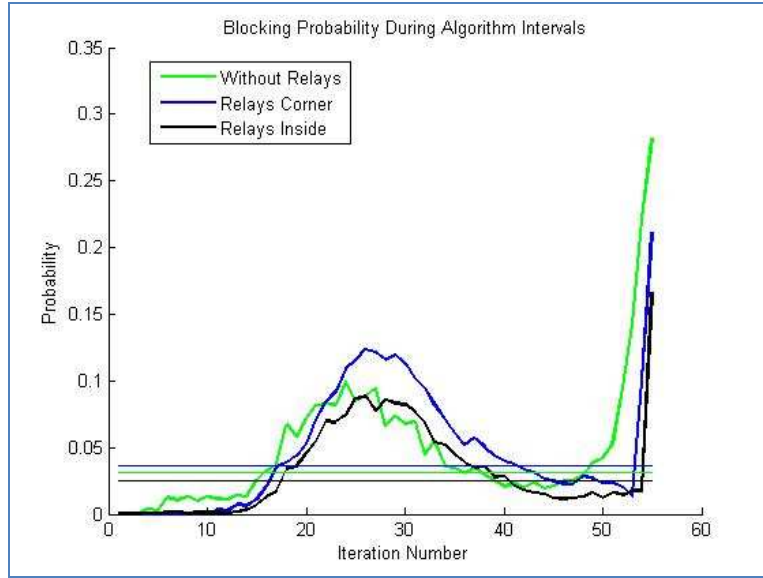
Fig. 25 - BLOCKING PROBABILITY DURING SIMULATION

5.4.- 2 PEAK PATTERN WITH A HOT SPOT

In the case with the hot spot in the centre of the scenario, the results are similar with the previous case but with smaller differences between the non-relaying and the relaying deployments.
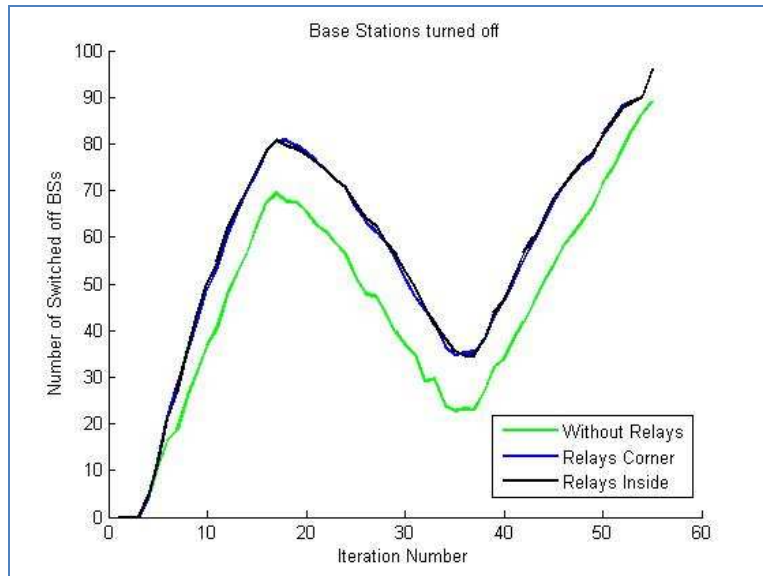

Fig. 26 - NUMBER OF BASE STATIONS TURNED OFF DURING SIMULATION

Again, the deployment with relay stations in the corner of the cells achieves the most energy saving. In this case, though, the average energy saving achieved with the non-relaying scheme is greater than the one achieved with deploying the relays inside the cell.
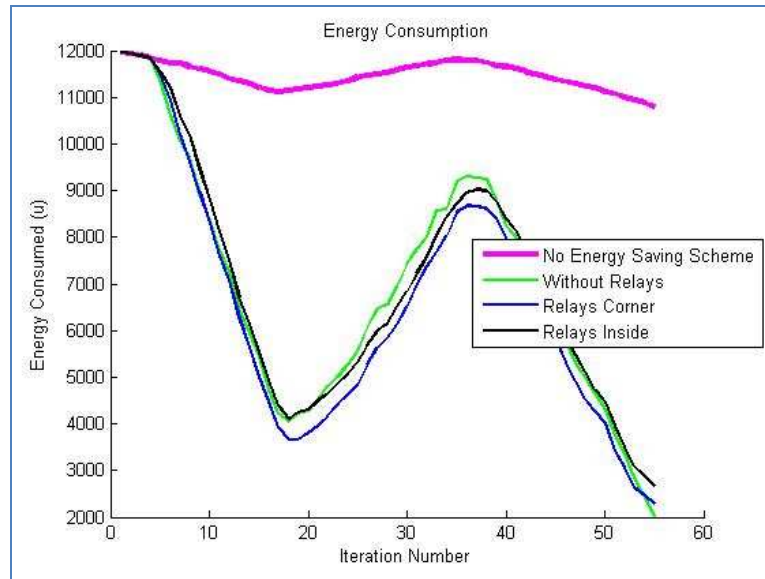
Fig. 27 - ENERGY CONSUMPTION DURING SIMULATION

Average Energy Saving Achieved	With respect to No Energy Saving Scheme	With Respect to No Relaying
No Relaying	39.67%	-
Relays in the Corner	42.89%	5.99%
Relays Inside	38.83%	-2.23%

Fig. 28 - ENERGY SAVING RELATION BETWEEN DIFFERENT DEPLOYMENTS

Differently from the previous case, the non-relay deployment is the scenario with the higher dropping probability, while there are no significant differences between the two relaying schemes. Like in the previous case with the hot spot, at the beginning of the simulation, with a higher traffic the dropping probability is above 1%.
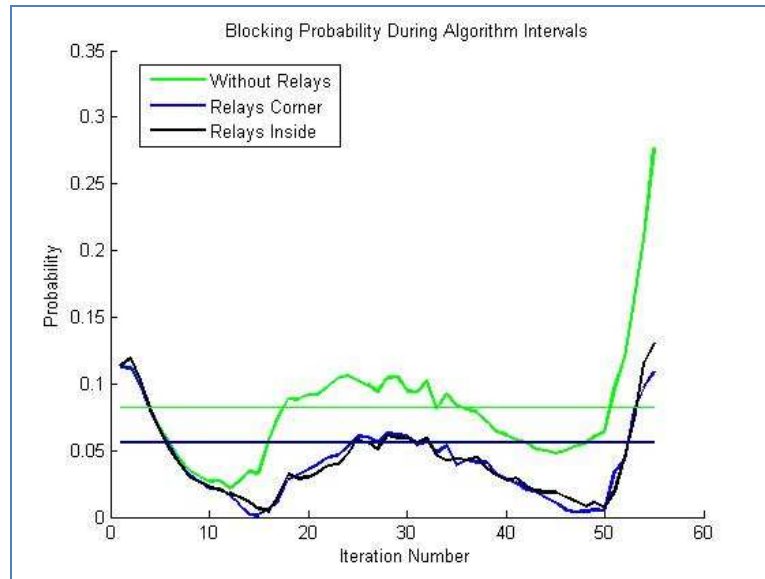
Fig. 29 - BLOCKING PROBABILITY DURING SIMULATION

6.1.- CONCLUSIONS

- The proposed simple algorithm achieves approximately 40% to 50% of energy saving when there is significant variation in traffic demands during the day.

- Relays are an efficient way to guarantee coverage in switching-off schemes, this is, to assume the traffic of neighboring cells when these are turned off. Instead, no significant gains are achieved in terms of capacity by using relays.

- RS deployed inside the cell yield better performances in terms of blocking probability, but consume more energy.

- RS deployed in the corner of the cells achieve the most energy saving, but the differences with the other deployments are not significant.

6.2.- FUTURE WORK

Due to limited time, the simulation has many simplifications that can change significantly the results, especially the issue of the interference. Relays operating in the same band as the base stations introduce interference in the system, which increases with the number of relays deployed. Therefore, it would be interesting to see the results that yield the same scenarios taking into account the interference caused.

In the scenarios simulated, though there are differences between non-relaying and relaying deployments, these are not very significant. It would be interesting to see the obtained results if the dropping probability is limited to 1% for the whole simulation. Intuition says that, in that case, to guarantee coverage and limit the dropping probability, the non-relaying scenario would switch off less base stations than the relaying deployments, thus achieving significant differences in the energy saving.

In the current work, relay stations have been used exclusively for coverage extension. In the hot spot scenario during the higher traffic periods, the dropping probability was higher than average. It would be interesting to allow the relay stations to be on this situation and use them for load balancing.

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