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Survey and Comparative Analysis of Energy Saving Mechanisms for LTE-Advanced Femtocells

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***Abstract*— In this paper we study dynamic energy saving mechanisms for the Long Term Evolution Advanced system (LTE-Advanced) with user-deployed cellular base stations (a.k.a. femtocells). In particular, we present a thorough review of different energy-saving approaches specific to LTE-Advanced networks, presenting existing component-level and system-level energy-saving techniques. Based on this review, we subsequently investigate 6 different mechanisms for dynamic cell deactivation and we evaluate them based on a) the user load in the cell, b) the traffic model, and c) the user mobility.**

***Index Terms*— LTE-Advanced, energy-saving, femtocells, comparative study**

I. Introduction

Energy saving is one of the most important issues that should be taken into account in the development of the Beyond 4G wireless communication systems. Mobile users are increasingly using data services. Therefore, more and more wireless infrastructures need to be deployed to cope with the heavy load, requiring an increasing amount of energy [1]-[5]. Numerically this means that the volume of network data is expected to increase every five years by a factor of 10 that is associated with an increase of 16-20% of energy consumption. In addition, as already mentioned, the femtocells are installed by the users and there is a large overlap between the energy required for femtocells and energy required for macrocells. Consequently, the number of base stations increases with the development of LTE-A and, according to surveys, the number of femtocells is expected to be ten times more than macrocells within the next few years. According to existing reports, higher consumption occurs at the base station part as compared to that required to support other components of a provider's network. Thus, mobile companies face the problem of increased consumption when developing their network. It is vital, therefore, to develop energy-efficient technologies to enable companies to meet the energy-saving challenge.

Base stations are designed to operate at maximum load and maximum performance. However, in practice, the load at a base station is not constant at all times of the day. In a dense urban area, for example, the highest usage rate is between 18.00 and 24.00 [6]. The fact that the remaining 18 hours of a sub-station is used makes it possible to use various techniques to improve the station's energy efficiency without affecting the traffic load [7]-[10]. Energy savings on base stations can be done on two levels: either at the component level, or at the system level. At the component level, some of the key parts of the base station can be deactivated to minimize energy consumption opportunistically. Instead, at the system level, a number of stations are deactivated and the load is distributed to neighboring stations to operate with only the minimum necessary stations.

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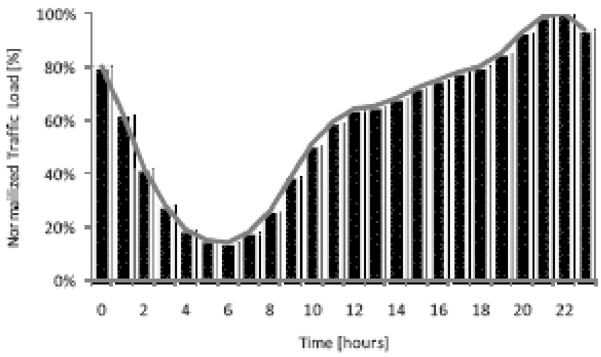


Fig. 1: 24hr distribution of the mobile data traffic in a dense urban environment.

To the remainder of this paper, we contribute with the following technical contribution in the respective area.

- ✓ We categorize, overview and compare existing energy saving techniques for femtocell-overlaid LTE networks, providing detailed discussions on their main differences and their practical use in real-life networks.
- ✓ We overview and formulate the problem of discontinuous reception (DRX) and dynamic cell deactivation for energy saving in femtocell networks.
- ✓ We formulate and detail different mechanisms that can be used to enhance the energy fingerprint of a femtocell overlaid network through the employment of dynamic cell deactivation, inspired by the employment of existing back-off mechanisms.
- ✓ We provide a comprehensive comparative analysis of the proposed energy saving mechanisms focusing on their performance under different network conditions, i.e. user load, traffic model, user mobility.

The remainder of this paper is organized as follows. In section II we categorize, overview and compare existing energy saving techniques for femtocell-overlaid LTE networks. In section III, we formulate and detail the problem of DRX in femtocell networks, whereas in section IV we present different mechanisms for dynamic cell deactivation in femtocell networks. In section V, we provide our comparative analysis for the proposed DRX mechanisms, while in Section VI we draw our conclusions.

II. OVERVIEW OF ENERGY SAVING MECHANISMS

In this section, we present the two different categories of energy saving mechanisms for femtocell overlaid LTE-A networks: component-level energy saving and system-level energy saving. In section II.A we detail the main options for component-level energy in femtocell networks, whereas in section II.B we overview different approaches for system-level energy saving.

A. *Component-level energy saving techniques*

In general, the power consumption of a base station (BS) is dominated by its radio unit [6]. The radio communication part is particularly important as it provides a natural interface between mobile users and the network. Continuous flow of information should be ensured while providing sufficient quality of service. In order to reduce the power consumption of radio communication effectively, it is necessary to calculate for each element the energy consumption that requires and to subsequently emphasize the main energy-hungry parts.

Figure 2 illustrates a simplified diagram of a base station transceiver of a femto-cell, with multiple transceivers, antennas and antenna interfaces (L). Each transceiver consists of a Power Amplifier (PA), a Radio Frequency Transceiver (RF) transceiver for both downlink (DL) and uplink (UL) reception, a baseband interface (BB) for both downlink (DL) and receive in uplink (UL) and a DC-DC power regulator.

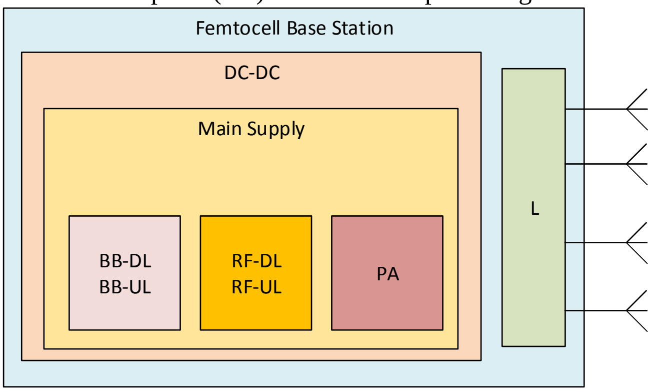


Fig. 2 Simplified Component-level diagram of a femtocell base station

According to existing reports, macrocell base stations consume a large percentage of their energy at their power amplifier units [6]. However, as the cell size decreases, the consumption of the power amplifier seems to be shared by the baseband signal processor (BB) and the RF transceiver (RF). Thus, femtocell-specific techniques for component-level energy saving should focus mainly on the PA, BB, RF elements.

1) *Energy Saving at the base band unit processor*

As the cell size decreases and the signal processing complexity increases, the power consumption in the digital baseband is becoming more and more dominant. Therefore, optimization of energy efficiency for the digital baseband is important. The basic technique focuses on energy scalability, both in the changing wireless environment and changing user demands such as system load. Baseband signal processing can be divided into many components. Some of these are a) time domain processing, for uplink and downlink filtering and sampling, b) frequency field processing, modulation / demodulation or equalization, channel encoding / decoding. These components are capable of adapting energy (EA) according to the signal load (the output power to the maximum transmission power). Adjustment is done by varying bandwidth, configuration, coding rate, antenna number, etc.

2) *Energy Saving at the analog RF transceiver*

The power adjustment in the RF transceiver is specified by the software (software-defined radio - SDR). This SDR technology is typically based on a simple zero-IF architecture, which can easily redefine all its analog components. This flexibility allows adjustments to the broadcast with different specifications and operating conditions. The transceiver provides flexibility in operating frequency and additionally controls filtration and amplification in the changing stages of the transmitter and receiver. This control is important in the context of optimization of energy, as well as the bandwidth and gain / SiNAD (signal to noise ratio and distortion) performance are the main elements for the adjustment of energy. At macrocell base stations, the RF transceiver has a fixed SINAD performance value, regardless of the signal load. From the point of view of energy consumption, however, it is more convenient to adjust the transceiver depending on the load so as to provide a good enough SINAD performance continuously for femtocell base stations.

3) *Energy Saving at the Power Amplifier (PA) unit*

At the femtocell base stations the power amplifier is not the main consumption element as in the macrocells. However, due to the spectral mask constraints and the lack of digital pre-propagation techniques, the peak to medium power radio (PAPR) ratio should increase, causing the amplifier power to drop significantly. The idea of an adaptive, energy-efficient amplifier is proposed to lead to a reduction in power consumption when the RF output power is less than the maximum. The main energy saving options here are:

• Adjusting the operating point. The power amplifier's operating point is optimized according to the required RF output power level (signal charge). At the same time, the specifications for spectral mask and PAPR are met.

• Disabling the power amplifier stages. By activating a fast switch between active and inactive on the RF power of the transistor, the consumption is reduced to a minimum when no RF output power is required.

B. *System-level energy saving techniques*

Macrocell base stations are typically designed for maximum performance giving minimum emphasis on energy-efficient and adaptive operation. To this end, the power consumption of a macrocell base station does not change depending on the station's load, but remains high [7]-[9]. However, because the station's load is not fixed during a regular 24hr period, energy saving at the system-level can be employed by dynamic tuning the base station and the mobile devices depending on the network status (e.g. current traffic load, user mobility, etc). Accordingly, network energy savings at a system-level (i.e. covering multiple base stations at the same time) can be made by reducing the power time of the power amplifiers, shrinking the bandwidth used, or even disabling the base station. At the system level of an LTE-Advanced system, the main energy saving techniques can be categorized based on the domain of operation that is fine-tuned in light saving more energy, i.e. time domain, frequency domain, spatial domain.

1) Time domain energy-saving

The LTE-A solutions in the time domain include temporarily disabling the power amplifier at a base station when there is no downlink data at that time. However, the base station should transmit reference signals (RS), i.e. pilot signals used for mobility management among others, and control signals even when there is no movement or is reduced. Therefore, the power amplifier is only temporarily disabled. Energy saving in the time domain is calculated according to the amount of time the amplifier is deactivated over a period of time, usually in a frame. There are three basic ways to temporarily turn off a power amplifier: a) deactivating the amplifier when the signal being transmitted does not include a signal-free symbol, b) using a multicast broadcast single frequency network (MBSFN) subframe to reduce the reference signals, c) discontinuous transmission (DTX) to further reduce the reference signals.

Referring to the deactivation of the PA when the transmitted symbols do not contain a signal, the simplest approach is to turn off the amplifier in the space where it will not have some information to send. However, although the switch-off is immediate, it takes about half a time for the amplifier to turn on again, as long as a symbol lasts. Taking this time into account, at least 47% of the frame time, the amplifier should be active for the transmission of reference signals and control signals [8].

Referring to the use of an MBSFN subframe, it should be said that the structure of an MBSFN framework is commonly used to provide services such as television on mobile devices using the LTE infrastructure. Thus, it is possible to send the same data to multiple users in different cells above the same synchronized frequency. In an MBSFN framework, the reference signals are one rather than two as in a single frame. Thus, the amplifier can remain off for longer.

Referring to the employment of Discontinuous Transmissions (DTX), the DTX approach may further reduce the reference signals relative to the MBSFN approach. If there is no downlink data stream, in discontinuous mode, no transmission is required in the frames. Nevertheless, discontinuous transmission reduces the reference signals beyond a level that, if not properly planned, it can cause non-standard operation to the mobile devices.

2) Frequency domain

In the frequency domain there are mainly two approaches to saving energy: either to reduce the utilized bandwidth, or to exploit the carrier aggregation feature available in LTE-A Rel. 10. In both cases, we can argue that the frequency domain energy saving techniques have a smaller impact on the operation of mobile devices but at the same time, they exhibit limited energy savings.

Referring to the reduction of the utilized bandwidth, since LTE-A supports a set of different bandwidths for transmission, a base station can change the bandwidth of the channel whenever necessary. The bandwidth reduction technique adjusts the downlink bandwidth and thus, if the load is low, the channel bandwidth may be shrunk so that less power is consumed, i.e. less bandwidth requires less radiation power. In addition, less bandwidth requires a reduced number of reference signals. For example, when the bandwidth changes from 10 MHz to 5 MHz, the transmit power may be reduced by about 3 dB. However, provided that this approach does not deactivate the PA unit, the consequential energy savings may be low.

Referring to the carrier aggregation technique, at a base station the carrier are organized into groups where each group is served by a different power amplifier. The idea is that when a group does not have a scheduled transmission in the downlink, the amplifier of the corresponding group can be deactivated. This approach, can only be applied to base stations with different power amplifiers for each group of carriers.

3) Spatial Domain

Approaches in the spatial domain do not only concern a base station of a specific radius or technology, but can be applied to heterogeneous networks and are more flexible. The main energy saving techniques in the spatial domain either a) reduce the number of antennas in a base station, or b) deactivate cells in multiple cell areas, or c) exploit the multi-tier network layout for burden sharing

Reducing the number of antennas is the most common technique used to save energy in the spatial domain. It is used for cases where the load in a cell is low and the antennas and consequently the power amplifiers connected to them can be deactivated. However, the reduction in the number of antennas also reduces the size of the cell, since the total power output is reduced. Therefore, some extra mechanism is needed to maintain signal strength at the ends of the cell. This energy saving approach can degrade or interrupt service delivery as it needs to be reformatted. Besides, mobile devices should be properly updated for all changes made to the base station, otherwise the operation of mobile devices will be affected.

On the other hand, the cell deactivation approach can be applied in areas where there are a large number of cells with evident overlaps between them. In addition, there is no need to readjust the base station components, such as the power amplifier. Whenever there is a reduced load in a cell, the base station is deactivated and the load of the serving users is transferred to the neighboring stations that are in operation. This station can be switched on again when there is an increased load. The signaling for switching on / off a base station can be done either between adjacent base stations or through the backbone network. Although the cell deactivation approach seems to save enough energy, there are several limitations. Firstly, frequent rotation of the base station affects the quality of service (QoS) experienced at the mobile devices. Secondly, mobiles should consume more power to connect to base stations that are farther away. Thirdly, disabling a station may create gaps in coverage, requiring active neighboring stations to increase their broadcasting power to cover this area. This extra consumption may be as much as the energy-saving gain from disabling the plant.

Exploiting the multi-tier network layout is done by combining different systems that serve the same set of mobile devices [11] [12]. Different tiers may use different wireless technologies. Assuming a two-tier structure, where one level includes the macrocells and the other the femtocells, we can argue that, since the femtocells are closer to mobile devices, they require less transmit power to maintain signal quality than macrocells. Thus, a mobile device saves more energy when connected to a femtocell. At the same time, macrocells can reduce their energy consumption by reducing the load and by applying various energy-saving techniques at the component level.

In Table 1, we provide a comparative analysis of the main approaches for system-level energy saving.

Table 1: Comparative analysis of system-level techniques

	Deactivate PA	Use MBSFN	DTX	Reduce BW	Carrier Aggreg.	Reduce #Antennas	Deactivate Cells	Multit-tier Structure
Deactivate basic BS components	x	x	x		x	x	x	
Requires adjustments at the end devices			x					
Only for HetNets								x
Can create gaps in coverage		x	x	x				
Applies in overlapping coverage scenarios							x	x
Only for low traffic conditions	x	x	x	x		x		
Affects the performance of the end devices			x			x		
Requires signaling		x	x	x	x	x		

Each approach exhibits both positive and negative features, while it also provides different energy savings to some extent. To maximize the energy saving, hybrid solutions can be implemented by combining approaches from different fields. As mentioned before, approaches to the frequency domain do not bring so much savings when applied independently. So, it's best to combine them with energy saving approaches in the remaining domains (time or space) for greater network savings. Although the combination of approaches saves more energy, it should also be done taking into account the processing and signaling overhead required to readjust the system operation, so as not to reduce the performance of mobile devices and the robust operation of the network.

III. Problem Statement

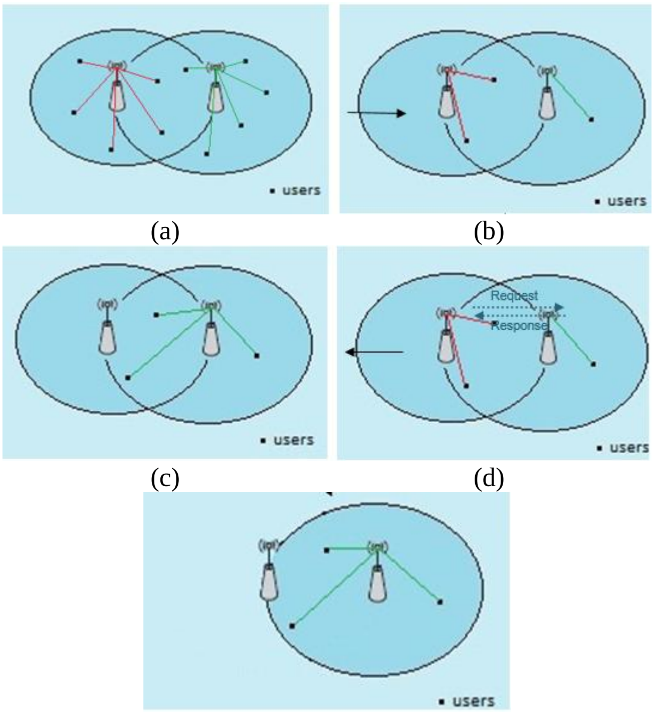
In this section, we define and formulate the problem of dynamic cell deactivation and discuss how it can be best applied to achieve greater energy savings while maintaining the quality of service at the end users. Section III.1 discusses why energy savings are needed in the network and why we choose the dynamic cell deactivation technique as a solution to the problem. In Section 4.2, we further present the parameters used in to dynamically deactivate cells using the DRX operation.

A. Problem Statement

The main reasons for employing energy-saving techniques in an LTE-A system can be summarized as follows.

- ✓ *Large number of femtocells*. The number of femtocells is expected to be six times larger than macrocells, since the users themselves place the base stations of the femtocells.
- ✓ *Base stations consume the most energy in the network*. 57% of the total energy of a mobile phone network is consumed at base stations and since femtocell stations will outnumber the network, energy consumption will increase.
- ✓ *Femto-cells are placed at random by users creating overlaps*. Femto-cells are developed by users and the position in which they will be placed is not specified. This creates large overlaps in the space between the femtocells.

These are the main three reason that make the problem of energy saving in a femtocell-overlaid network a critical one. Minimum consumption should therefore be achieved, while ensuring that user services are not degraded. The energy saving techniques to be applied should maintain the quality of the service that the user understands above some desired thresholds. Depending on the network structure and the user habits, a specific technique, or a combination of techniques, may reduce the total energy consumption more than another. Since the number of femtocells increases with no signs of saturation in the future and the overlap between the cells is already evident, the potential of disabling cells for certain intervals when the user load is reduced can save enough energy on its part network. Deactivation of a cell is made after a coordination phase with neighboring cells on whether the users can be transferred to them. Below is an example of a network with two femtocell base stations.



(a) (b) (c) (d) (e)

Figure 3: Energy Saving example

It can be seen that one can be deactivated in consultation with each other. At peak hours, e.g. at 19:00 in the afternoon, the two base stations are in full operation, since there are enough users in their range (Figure 3a). However, when there are not enough active users, e.g. at 2:00 in the evening, the two stations are under-running and consuming unnecessary energy (Figure 3b). Whenever a station has low traffic, it can check periodically whether neighboring cells can serve users within its reach. Thus, there is an understanding with the exchange of information between the two neighboring cells to check if users can be transferred from one cell to another (Figure 3c). If all users of the first cell are moved to the neighboring (Figure 3d), then the base station can be disabled by saving energy (Figure 3e).

B. DRX Formulation

The Discontinuous Receiver (DRX) technique is applied to the receiver when there are no packets to download or to send [14]-[16]. In the discontinuous receiver, the receiver remains active for specific subframes for signaling the base station and then switches off for a certain amount of time. This process continues periodically until packets arrive at the receiver. If a packet appears during the time that the discontinuous shutdown mechanism is activated, i.e. when the receiver is not active, the packet will suffer a delay that depends on the length of the DRX cycle. In the following, we present a set of parameters for the discontinuous reception mechanism, which are defined by the network according to the quality of service required by each application.

- **ON duration timer**: the number of frames where the receiver will be active and will be signaled from the base station. This time is set at the beginning of the DRX cycle before the receiver enters the power saving mode.
- **Short DRX cycle (DRX cycle)**: is the first DRX cycle that is applied after activating the discontinuous reception.
- **DRX short cycle timer**: expressed in a number of small DRX cycles, it measures the number of small circles that will be skipped until the employment of a large DRX.
- **Long DRX cycle**: Indicates the length of the long DRX cycle that is applied after a certain number of short cycles. The large DRX cycle is used to save more energy when there is no traffic for a long period of time.
- **DRX inactivity timer**: indicates the time period, expressed as a number of successive subframes, that the receiver has to wait before the discontinuous reception mode is activated. When the timer reaches the maximum value, the receiver activates the DRX mechanism.

The aforementioned set of parameters are illustrated in Fig. 4.

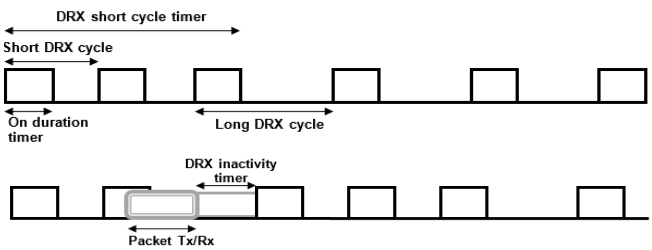


Figure 4: DRX parameters

The dynamic cell deactivation should be chosen so as to operate in a similar way with the DRX mechanism presented in Fig. 4. Optimal energy savings on the network should be maintained while keeping the flow of information while providing sufficient quality of service to users. The parameters for the dynamics of cell deactivation are as follows:

- **Active Duration Time** (***T_{on}***): is the time that the cell stays active, waiting to receive a user's handover signal from an adjacent cell. This time will be constant and will be repeated periodically, depending on the cycle length applied.
- **Inactive Time** (***T_{off}***): is the time the cell is switched-off to save energy. During this time the cell does not serve any user, there is no communication with the neighboring cells and cannot see if a user is within its reach. It should be ensured, therefore, that neighboring cells can serve users likely to appear in the area as long as this cell is switched off without compromising the quality of user services.
- **Cycle length** (***T_{cycle}***): essentially represents the sum of the two previous years, T_{on} + T_{off}. This is the time period between two consecutive cell activations, as shown in Figure 5. This time period varies depending on whether there is user traffic changing the T_{off} time. In particular, initially the cycle duration will be small and if a user does not appear in the hive for a certain number of cycles then it can be increased. Increasing the duration of the cycle will not be continuous, but there will be a maximum value, which when taken will remain constant. Additionally, if there is a referral from a user, the cycle time will be reduced so as not to affect the performance of the network.
- **Number of rounds of equal duration (*N*)**: expressed in a number of cycles and indicates the number of cycles of equal duration to be spent, until the cycle duration increases. This number is not fixed but varies as we increase the cycle duration.
- **Inactivity time (*T_{idle}*)**: is the time between the moment that the last user moves to another cell and the moment until the shutdown mode is activated. During this time, the cell remains active because there is a high probability that a neighboring cell is required to be handed over to a user and thus reduce the delay that can occur if the cell is deactivated immediately. This time can be applied automatically by the base station and in the case where the base station detects a user traffic that is close enough to it and is served by a neighboring cell because there is also an increased handover probability.
- **Control timer** (***$T_{control}$***): The timer is activated when the station is active and serves users. Specifies the periodic moments during which the base station exchanges information with neighboring stations to check whether it can handover users to neighboring stations. This enables the station to ensure that the users within its reach are served by a neighboring cell when it is deactivated.

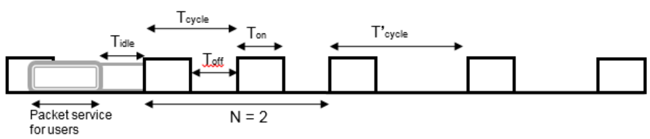


Figure 5: Parameters for dynamic cell deactivation

Section IV examines how we can dynamically adjust some of the above parameters, such as the cycle time, to save more power on the network while maintaining the quality of the service provided for active user connections.

IV. CELL DEACTIVATION MECHANISMS FOR FEMTOCELL NETWORKS

This section discusses six different design options for dynamic cell deactivation, which follow from linearly, or exponentially adjusting the cell deactivation timers presented in the previous section. To achieve enhanced energy savings depending on the user traffic, we can change some parameters for the dynamic deactivation of cells. In particular, we can increase the duration of the cycle, i.e. the inactivity time of the T_{off} timer, after a number of N rounds of equal duration assuming that no user is required to be handed over to another cell. The increase can be done either linearly or exponentially, depending on the area where the cell deactivation or the user movement takes place. If during the time where a station is active, a neighbor base station requires a handover for some user in its proximity, then the inactivity timer T_{off} should be reduced aiming to avoid service degradation. In a similar manner, the reduction of T_{off} can be exponential, linear or be reduced to the minimum possible time of inactive duration. The combinations of the above cases are discussed below.

In addition to this parameter, the number of equal-length cycles N could also be readjusted. N can remain constant, increase or decrease after some time. To this end, we study what is the most appropriate value of the N parameter, depending on the traffic of the cell under scope. Another parameter that needs to be studied is the maximum time that the base station may remain inactive. As mentioned before, the T_{off} timer may be increased, but a maximum T_{max} value should be set as above, so that there is no reduction in the QoS if the station remains inactive for some time. The most appropriate value for the maximum inactive time T_{max} may occur depending on the movement of the users in the cell area.

In the sequel, we assume that the parameter N remains fixed and does not change. The same assumption is made for T_{max}, which is also left as future work. An additional system parameter is the time T_{min}, which is defined as the minimum amount of time that a cell may be inactive. Thus, the maximum inactive time T_{max} is defined as a multiple of the time T_{min}. Finally, a timer Z is used, indicating the current number of cycles that have passed prior to the employment of the dynamic cell deactivation, so that in conjunction with the number N, the time upon which the T_{off} time should change.

Accordingly, in the following we investigate six different design options for adjusting the inactivity timer T_{off}

Option 1. Linear increase and linear decrease of T_{off}.

Option 2. Linear increase and exponential decrease of T_{off}.

Option 3. Linear increase and decrease to the minimum possible value for T_{off}.

Option 4. Exponential increase and linear decrease of T_{off}.

Option 5. Exponential increase and exponential decrease of T_{off}.

Option 6. Exponential increase and decrease to the minimum possible value for T_{off}.

A. *Linear increase and linear decrease of T_{off}.*

As mentioned above, during the dynamic cell deactivation alters the timer T_{off} is readjusted when for notable number of cycles no user movement is observed in the cell. Thus, for this specific option, after N cycles of equal duration, the T_{off} timer will increase by a c T_{min} parameter until it reaches the upper limit T_{max} set by the system. Each cycle increases the number Z by one and then calculates the time T_{off} with the following formula:

$$T_{off} = \begin{cases} \min(T_{off} + c \cdot T_{min}, T_{max}), & Z \bmod N = 0 \\ T_{off}, & \text{Else} \end{cases} \quad (1)$$

During the time the cell is active, a user may be handed over (HO) to a neighboring cell. The cell stays active for as long as it has users to server and simultaneously readjusts the dynamic cell deactivation parameters. For the time that the cell has at least one user to server, the cell deactivation process is virtually running by reducing the idle time (even if the station is not deactivated). The next cycle that will be implemented after completing the user service should have a reduced inactive time duration than it used to before, to ensure the smooth operation of the network and the quality of user services. Thus, in this design option, the T_{off} time is reduced by a parameter c T_{min} according to the formula:

$$T_{off} = \begin{cases} \max(T_{off} - c \cdot T_{min}, T_{min}), & Z \bmod N = 0 \\ T_{off}, & else \end{cases} \quad (2)$$

When user service time is over and there are no users in the cell coverage, the cell remains active for T_{idle} time. After this time, the number Z is reset and the active time of Tone dynamic deactivation time with the T_{off} parameter reaches the reduced value that has occurred. An example of the above function is shown below:

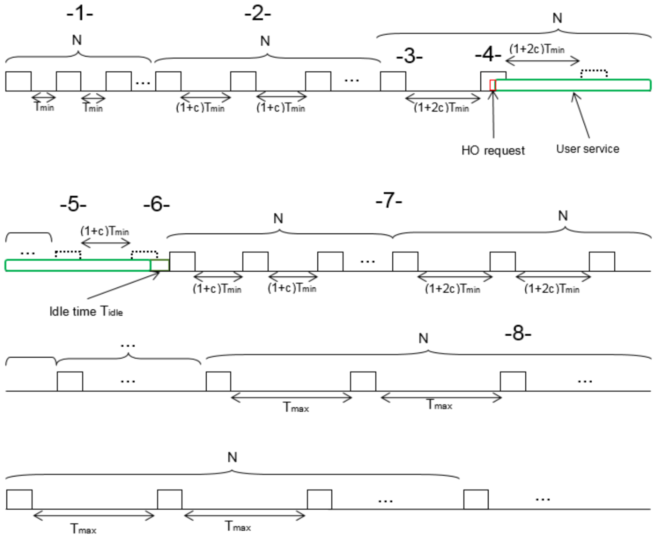


Figure 6: Option 1 runtime example

The steps of dynamic cell deactivation followed in the example above are as follows:

-1- The function starts with the active duration and then follows the minimum idle time T_{min}. In each cycle the inactive time is recalculated, but after N cycles it is not changed.

-2- After N cycles have passed without a HO request, at the beginning of the next cycle the value of Z is set to $Z = N$ and the inactive duration is calculated according to the first branch of the formula (1) and thus increases by c T_{min}.

-3- Similarly, for N cycles, the value of the inactive time is constant with $T_{off} = (1 + c)\ T_{min}$. At the beginning of the next cycle, the number Z has a value of $Z = 2N$ and since there is no request for handover, the inactive duration time is increased by $c\ T_{min}$ and now has a value $T_{off} = (1 + 2c)$ Tmin.

-4- At the time of active request a handover of some user to the cell is requested. As long as the station serves a single user, it does not turn off, but the dynamic switch off parameters of the cells change. The cycles are "running" like before, and so in the next virtual cycle the inactive duration time is again calculated with $Z = 2N + 2$. Because there is user service, time comes from the second branch of type (2) and remains constant.

-5- After N cycles with T_{off} = (1 + 2c) T_{min}, Z is set to Z = 3N and the time of inactive duration changes. Because there is user service, time is reduced by c T_{min} according to the first branch of formula (2) and will have a value T_{off} = (1 + c) Tmin.

-6- When all users within the cell range moved to neighboring cells and the cell does not have a user to serve, it remains active for time T_{idle}. Then, after the Z number is reset, the cell deactivation potential is activated, with an inactive time value of the value resulting from the reductions that occurred during the time of service.

-7- After no HO request, each N cycle time of inactive duration is increased by c T_{min}.

-8- The idle time increases and reaches the maximum time T_{max}. After N cycles with $T_{off} = T_{max}$ and since there is no request for relaying some user, the inactive duration time for the next N cycles will have to be calculated again, but because the maximum time remains T_{max}. So for the following cycles, the time remains fixed at T_{max}, until a HO request is made.

B. Linear increase and exponential decrease of T_{off}

In this design option, increasing the T_{off} time is done in the same way as before. That is, the T_{off} time is increased by one parameter c T_{min}, after N cycles of equal duration, until it reaches the upper limit T_{max} set by the system. In each cycle the number of Z increases by one and the time of inactive duration T_{off} is calculated based on (1). When the cell is active and serves some users, the T_{off} parameter decreases exponentially by a parameter k. Thus, the time T_{off} is calculated by the formula:

$$T_{off} = \begin{cases} \max\left(\frac{T_{off}}{k}, T_{\min}\right), & Z \bmod N = 0 \\ T_{off}, & else \end{cases} \tag{3}$$

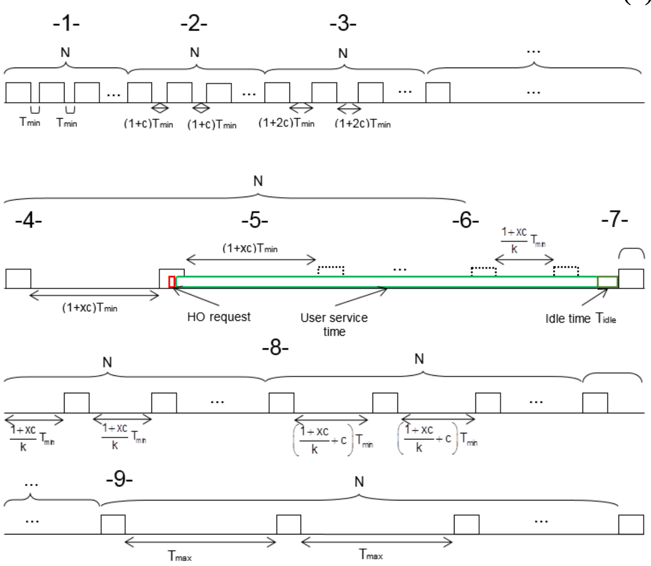


Figure 7: Option 2 runtime example

When the user service time is over and there are no users in the cell range, the cell remains active for T_{idle} time. After this time, the number Z is reset and the active time of T_{on} dynamic deactivation time with the T_{off} parameter reaches the reduced value that has occurred. An example of the above dynamic cell deactivation mechanism is shown in Fig. 7. The steps of this dynamic cell deactivation mechanism are as follows:

-1- The mechanism starts with the active duration and then follows the minimum idle time T_{min}. In each cycle, the inactive time is recalculated, but if N cycles will not pass, the T_{off} time is not changed.

-2- After N cycles have passed without HO request, at the beginning of the next cycle the value of Z becomes $Z = N$ and the inactive time is calculated according to the first branch of formula (1). Thus, it increases by c T_{min} and has a value T_{off} = (1 + c) Tmin, which remains constant for subsequent N cycles.

-3- At the beginning of the next cycle, the number Z has a value of $Z = 2N$ and since there is no request for referral, the inactive time is increased by c T_{min} and takes a T_{off} = (1 + 2c) Tmin for the next N cycles.

-4- After several cycles have passed without a HO request, the value of the inactive duration time will be increased every N cycles and at the beginning of the next cycle it will reach the value of T_{off} = (1 + xc) T_{min}.

-5- During the on duration time, a HO request takes place. The cell remains active as long as it has users serve, while the parameters of dynamic cell deactivation are updated. In the next virtual cycle, the inactive duration time is calculated by the formula (3) because there is user service. The time comes from the second branch of the formula and it does not change.

-6- After N cycles with a constant value equal to T_{off} = (1 + xc) T_{min}, the value of the inactive duration time should be changed and since the cell has some users to serve, T_{off} will be reduced based on the first branch of the formula (3). The new value of the inactive duration time will be $T_{off} = T_{min}$.

-7- When all users within the range of the cell are handed over to neighboring cells and the cell does not have a user to serve, it remains active for the T_{idle} time. Then, once the Z number is reset, the cell deactivation option is activated with an inactive time value following from the reductions made during the time when user service was provided.

-8- In the absence of a HO request, the inactive duration time is increased by c T_{min} once per every N cycles.

-9- After a number of cycles without a HO request T_{off} will reach the maximum time T_{max}. For those circles that follow without a HO request, T_{off} remains fixed at T_{max} and does not further increase.

C. Linear increase and decrease to the minimum T_{off}

Since the increase is again linear and in this design option, T_{off} increases according to (1). However, when the cell is active and provides service to users, T_{off} decreases to the minimum possible value T_{min} according to (4).

$$T_{off} = \begin{cases} T_{\min}, & Z \bmod N = 0 \\ T_{off}, & \text{Else} \end{cases} \tag{4}$$

When the user service time is over and there are no users in the cell range, the cell remains active for T_{idle} time. After this time, Z is set to zero and the active time T_{on} is resumed. The T_{off} parameter is also set to T_{min}. This is similar to starting the cell deactivation process from the beginning. An example of the above function is shown below.

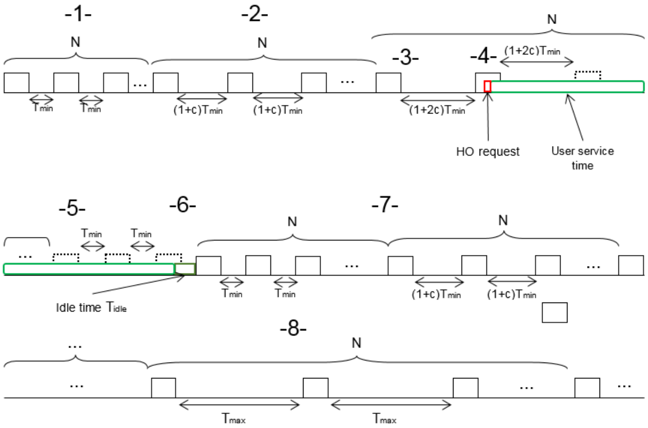


Figure 8: Option 3 runtime example

The steps of dynamic cell deactivation followed in the example above are as follows:

-1- The function starts with the active duration and then follows the minimum idle time T_{min}. In each cycle the inactive time is recalculated, but after N cycles it remains unchanged.

-2- After N cycles have passed without a HO request, at the beginning of the next cycle the value of Z becomes $Z = N$ and the inactive duration is calculated according to the first branch of the formula (1) and thus increases by c T_{min}.

-**3-** Similar to before, for N cycles, the value of the inactive time is constant with $T_{off} = (1 + c)\ T_{min}$. At the beginning of the next cycle, the number Z has a value of $Z = 2N$ and since there is no request for a HO, the inactive duration time is increased by c T_{min} and now has a value $T_{off} = (1 + 2c)\ T_{min}$.

-4- During the on time period a HO request takes place. As long as the station serves at least on user, it does not turn off, but the dynamic switch off parameters of the cells are updated. In the next virtual cycle, the inactive time is recalculated to Z = 2N + 2. Since there exists user service, T_{off} is set according to the second branch of (4) and remains constant.

-5- After N cycles with $T_{off} = (1 + 2c)\ T_{min}$, Z is set to $Z = 3N$ and T_{off} is updated. Since there is user service, T_{off} is set to T_{min} according to the second branch of (4).

-6- When all users within the cell range are handed over to neighboring cells, it remains active for T_{idle}. Then, after the Z number is set to 0, the cell deactivation process is activated and T_{off} is set to T_{min}.

-7- In the absence of a HO request, T_{off} increases by c T_{min} once per every N cycles.

-8- After an adequate number of cycles, T_{off} reaches the maximum value of T_{max}. In the absence of a HO request, the T_{off} parameter remains T_{max} for the remaining cycles.

D. Exponential increase and linear decrease of T_{off}

In this design option T_{off} increases exponentially. That is, T_{off} is increased by k after N cycles until it reaches the upper limit T_{max} set by the system. In each cycle the number of Z is increased by one and the inactive duration of time T_{off} is calculated based on the formula in (5).

$$T_{off} = \begin{cases} \min(T_{off} * k, T_{\max}),\ Z \bmod N = 0 \\ T_{off},\ else \end{cases} \quad (5)$$

When the cell is active and serves users, T_{off} is reduced linearly according to (2). When user service time is over and there are no users in the cell range, the cell remains active for T_{idle}. After this time, Z is reset to zero and the active time of T_{on} is applied again. T_{off} also takes the minimum value. An example of the above function is shown in Fig. 9.

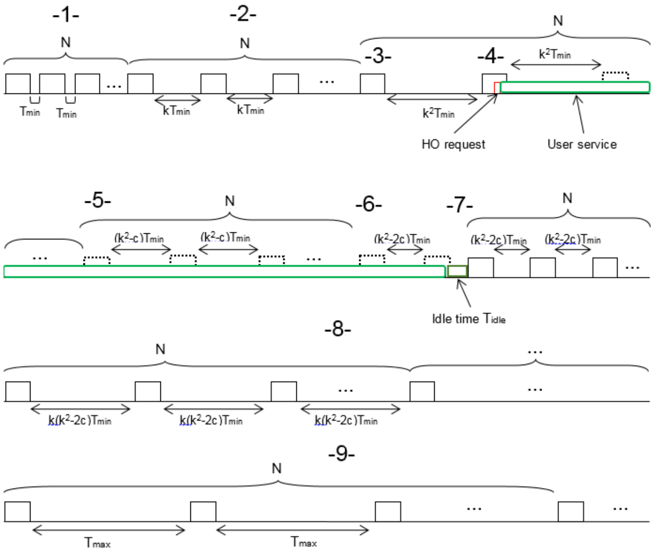


Figure 9: Option 4 runtime example

The steps of this option of dynamic cell deactivation are as follows:

-1- The function starts with the active duration and then follows the minimum idle time T_{min}. In each cycle the inactive time is recalculated, but after N cycles it is not changed.

-2- After the N cycles have passed without requesting a transfer, at the beginning of the next cycle the value of the number Z becomes $Z = N$ and the inactive duration time is calculated according to the first branch of the formula (5) and thus rises to $T_{off} = k\ T_{min}$.

-3- Similar to other options, for N cycles the value of the inactive time is constant with $T_{off} = k\ T_{min}$. At the beginning of the next cycle, the number Z has a value of $Z = 2N$ and since there is no request for handover, the inactive duration time is multiplied by k and takes the value off $T_{off} = k^2 T_{min}$.

-4- During the on time period a HO request takes place. As long as the station serves at least on user, it does not turn off, even though all parameters are being updated. In the next virtual cycle, the inactive time is recalculated to $Z = 2N + 2$. Because there is user service, T_{off} is calculated based on the second branch of type (2) and remains constant.

-5- After N cycles with $T_{off} = k^2\ T_{min}$, the number Z is $Z = 3N$ and the time of inactive duration changes. Since there is user service, T_{off} is reduced by c T_{min}, according to the first branch of the formula (2) and will have a $T_{off} = (k^2\text{-}c)\ T_{min}$.

-6- After N cycles, the inactive duration time will decrease again by c T_{min}, and will have a $T_{off} = (k^2\text{-}2c)$ Tmin.

-7- When all users within the cell range are handed over to neighboring cells, the cell remains active for T_{idle}. Then, after the Z number is reset to zero, the cell deactivation process is activated with T_{off} calculated by the reductions that occurred during the on service time.

-8- In the absence of a HO request, T_{off} is multiplied by k once per every N cycles.

-9- After an adequate number of cycles, T_{off} reaches to T_{max}. In the absence of a HO request, the T_{off} parameter remains T_{max} for the remaining cycles.

E. Exponential increase and exponential decrease of T_{off}

In this design option T_{off} increases exponentially according to (5). Moreover, when the cell is active and some users are served the T_{off} decreases exponential as well according to (3). When the user service time is over and there are no users in the cell radius, the cell remains active for T_{idle}. After this time, Z is reset to zero and the active time of T_{on} is applied again. T_{off} also takes the minimum value that may occur. An example of the above function is shown in Fig. 10.

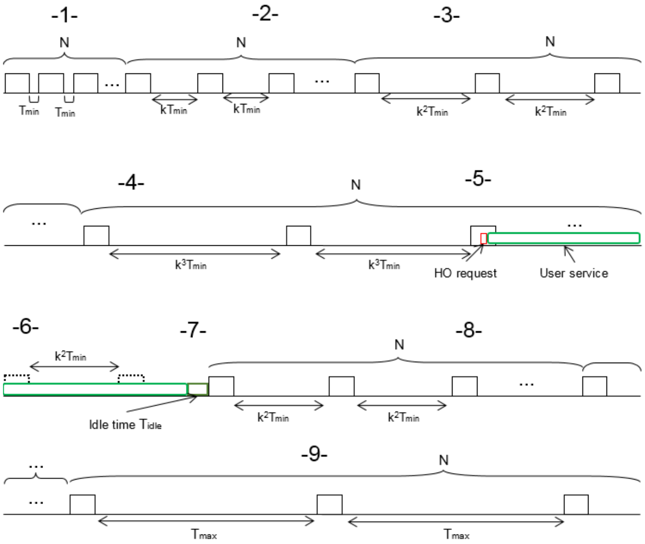


Figure 10: Option 5 runtime example

The steps of this option of dynamic cell deactivation are as follows:

-1- The function starts with the active duration and then follows the minimum idle time T_{min}. In each cycle the inactive time is recalculated, but after N cycles it is not changed.

-2- After N cycles without a HO request, at the beginning of the next cycle Z becomes Z = N and the inactive time is calculated by the first branch of (5) to $T_{off} = k\ T_{min}$.

-3- Similar other options, for N cycles the value of the inactive time is constant with $T_{off} = k\ T_{min}$. At the beginning of the next cycle, the number Z has a value of $Z = 2N$, and since there is no HO request, the inactive duration time is multiplied by k and now has a value T_{off} = k^2Tmin for the subsequent N cycles.

-4- In the absence of a HO and given Z = 3N, the inactive duration time is multiplied again by k to $T_{off} = k^3\ T_{min}$.

-5- During the on time period a HO request takes place. As long as the station serves at least on user, it does not turn off, but the dynamic switch off parameters of the cells are updated. In the next virtual cycle, the inactive time is recalculated to $Z = 3N + 3$. Because there is user service, T_{off} follows from the second branch of type (3) and remains constant.

-6- After N cycles with $T_{off} = k^3\ T_{min}$, the number Z is Z = 4N and the time of inactive duration changes. Since there is user service, T_{off} remains constant as in the second branch of (2).

-7- When all users within the range of the cell are handed over to neighboring cells and the cell does not have a user to serve, it remains active for T_{idle}. After that, Z is reset to zero, the cell deactivation process is activated again using the T_{off} calculated through the exponential decrease during the time of service.

-8- In the absence of a HO request, T_{off} is multiplied by k once per every N cycles.

-9- After an adequate number of cycles, T_{off} reaches to T_{max}. In the absence of a HO request, the T_{off} parameter remains T_{max} for the remaining cycles.

F. Exponential increase and decrease to the minimum T_{off}

In this design option T_{off} increases exponentially according to (5). Moreover, when the cell is active and the users are served T_{off} is set to the minimum value of T_{min} according to (4). When the user service time is over and there are no users in the cell radius, the cell remains active for T_{idle}. After this time, Z is reset to zero and the active time of T_{on} is applied again. T_{off} is also set to the minimum value of T_{min}. An example of the above function is shown in Fig. 11.

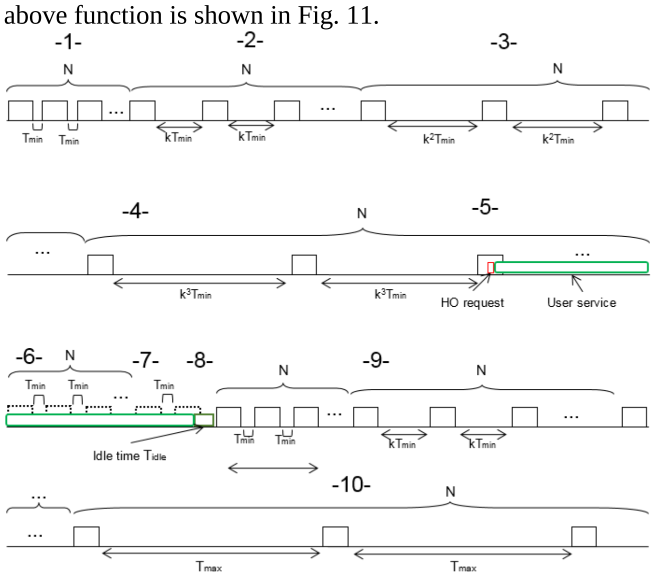


Figure 11: Option 6 runtime example

The steps of dynamic cell deactivation followed in the example above are as follows:

-1- The function starts with the active duration and then follows with the minimum idle time T_{min}. In each cycle, T_{off} is recalculated, but after N cycles it remains changed.

-2- After N cycles with no HO request, the value of Z is set to Z = N and T_{off} is calculated according to the first branch of the formula (5) and thus increases to $T_{off} = k\ T_{min}$.

-3- Similar other options, for N cycles the value of the inactive time is constant with $T_{off} = k\ T_{min}$. At the beginning of the next cycle, Z is set to Z = 2N, and since there is no HO request, T_{off} is multiplied by k and now has a value T_{off} = k^2Tmin.

-4- In the absence of a HO and given Z = 3N, T_{off} is multiplied again by k and becomes $T_{off} = k^3\ T_{min}$.

-5- During the on time period a HO request takes place. As long as the station serves at least on user, it does not turn off, but the dynamic switch off parameters of the cells are updated. In the next virtual cycle, the inactive time is recalculated to $Z = 3N + 3$. Because there is user service, T_{off} follows from the second branch of formula (4) and is set to $T_{off} = T_{min}$.

-6- After N cycles with $T_{off} = k^3\ T_{min}$, the number Z is Z = 4N and the time of inactive duration changes. Since there is user service, T_{off} remains constant by the second branch of (4).

-7- After N virtual cycles T_{off} remains the same to $T_{off} = T_{min}$.
-8- When all users within the range of the cell are handed over to neighboring cells and the cell does not have a user to serve, it remains active for T_{idle}. Then, after the Z number is reset, the cell deactivation dynamics is activated, with an inactive time value equal to $T_{off} = T_{min}$.
-9- In the absence of a HO request, T_{off} is multiplied by k once per every N cycles.
-10- After an adequate number of cycles, T_{off} reaches to T_{max}. In the absence of a HO request, the T_{off} parameter remains T_{max} for the remaining cycles.

V. COMPARATIVE ANALYSIS

This section includes a comparative study on the performance and suitability of the dynamic cell deactivation options described in Section IV under different network load, user traffic and user mobility scenarios that are relevant to the LTE-Advanced mobile data network architecture. From the design options presented in section IV, none of them should be considered as more energy efficient as compared to the others, which would give satisfactory results in all cases. The efficiency of each options depends on multiple factors such as the current network load in the serving cell, the peculiar characteristics of user traffic (including data-rate, latency requirements and so on) as well as the movement of the end users inside the cell radius. In the sequel, we provide a comprehensive comparative analysis between the different design options presented in section IV and identify the conditions under which one of them could provide superior performance as compared to the others, for the different types of scenarios and parameter values. Furthermore, for each scenario we indicate with an asterisk (*) the design choice that we consider the most appropriate, having as primary criterion the seamless support of the user QoS and as a second criterion the maximum possible energy saving of the network.

A. Different network load conditions

The user load in cell is not constant, but changes according to the time of the day that we observe it. Based on Figure 1, we can categorize the user load into three broad categories:

• **Low user load**, which corresponds to a load of less than 40%. As shown in Figure 1, for this specific network load distribution on a daily basis, it corresponds mainly to the evening hours 2:00-9: 00.

• **Medium user load**, which corresponds to a load of between 40% and 80% and corresponds to the intervals of the day between 9:00-17:00 and 00:00-2:00.

• **High user load**, which accounts for a load of more than 80% and corresponds to the afternoon hours mainly between 17:00-00:00 for this specific load distribution example.

During the day when the load on the users is increased (> 80%), the cell should not be switched off for long periods of time to ensure that all users have a good quality of service with tolerable delays and high data rate transmissions. In this case, therefore, we choose the dynamic cell deactivation options that apply a slow increase of the T_{off} timer, while having a fast decrease so that the intervals that the cell is inactive are relatively sparse. On the other hand, when the user load is low (<40%), the cell can be deactivated for a longer period of time to save energy without affecting the performance of the users, which can be served adequately served by neighboring cells. Finally, for medium load levels (40-80%), the idle time of the station should not be frequently increased to provide satisfactory service to all users within range of the cell. The above options are illustrated below in Table 2.

Table 2: Comparative analysis for different network load

	Low load	Medium load	High load
Option 1: Linear increase and linear decrease of T_{off}		x	
Option 2: Linear increase and exponential decrease of T_{off}	x	x*	
Option 3: Linear increase and decrease to the minimum T_{off}	x*		
Option 4: Exponential increase and linear decrease of T_{off}			x*
Option 5: Exponential increase and exponential decrease of T_{off}			x
Option 6: Exponential increase and decrease to minimum T_{off}		x	

B. Different application traffic type

The applications which we have chosen to include in our comparisons are a) Voice over IP (VoIP) calls over the internet, b) standard internet browsing, and c) online gaming. To select the most appropriate design option for these specific applications, we are interested in how easily the transmission of packets can be postponed and their transmission rate can be readjusted depending on the network status.

For the VoIP traffic model, the voice call process is described by a pattern consisting of speech and silence intervals. Experimental measurements of 10 phone conversations lasting 15 minutes each have showed that the activity rate during the conversation was 47.17%. Thus, there is a linear movement in packet transport, since it is a voice conversation and packet delay should be small enough to have a good quality of service.

On the other hand, the Internet browsing traffic model is one of the most complex models. Various measurements for HTTP traffic indicate that the vast majority of web pages are composed by relatively small objects. Each web page consists of a number of web objects, such as the main page, embedded images, executable applications, and various plug-ins. In the current bibliography, it is particularly common for the time interval between the access into two different websites to be modeled based on the exponential distribution. Exponential distribution is considered to be a satisfactory model of time thinking and includes the time the user needs to read the whole or part of the site. In addition, any service delay does not significantly affect the quality of the application service.

Finally, for online games, there are several types of games with varying requirements for the support they need from the network. In particular, real-time games are mostly sensitive to the quality of service they require. Therefore, if users in the cell use such applications, there is likely to be a continuous flow of packets and the delay requirements are very strict.

Table 3: Comparative analysis for different user traffic

	VoIP	Web browsing	Online gaming
Option 1: Linear increase and linear decrease of T_{off}	x		
Option 2: Linear increase and exponential decrease of T_{off}	x*		
Option 3: Linear increase and decrease to the minimum T_{off}	x		x*
Option 4: Exponential increase and linear decrease of T_{off}		x*	
Option 5: Exponential increase and exponential decrease of T_{off}		x	
Option 6: Exponential increase and decrease to minimum T_{off}			

C. *Different user mobility*

Modeling of user mobility is based on the speed at which a user moves into the cell range. The mobility classes defined by the ITU are as follows:

• **Pedestrian** if the user's speed is from 0 to 10 km / h.

• **Passengers on a vehicle** if the user's speed is from 10 to 120 km / h.

• **Passengers on a high-speed vehicle** if the user's speed is from 120 to 350 km / h.

The decision on which design option should be applied to each mobility class is more difficult to obtain than the previous criteria (user load, traffic model). This is because there are two approaches to the behavior that the cell may exhibit in each class. In particular, a pedestrian user will statistically stay longer in the range of a specific cell. Additionally, if it moves to a neighboring cell, it is likely to return to the previous one, since it will be close to the boundaries of the two cells. So the intervals that the cell may be deactivated should be small, and the reduction of the idle time should be done swiftly. On the other hand, the cell may request a pedestrian to be transferred to a neighboring cell and be deactivated for a longer period of time, provided that the user's speed is small and its traffic can be adequately served by the neighboring cell.

Similarly, although a user on a vehicle can be assumed to remain an adequate period of time within the range of the cell, this time interval should not be large. Thus, the inactive cell duration should not be frequently adapted (ie a linear reduction is more suitable). The second approach of a user on a vehicle is that the user who moved to a neighboring cell because of its speed will soon be out of reach and again should be served by the another cell. Thus, reducing the inactive time should be done swiftly so that the cell will be active to serve the user needs.

Table 4: Comparative analysis for different user mobility models assuming coordination between neighboring cells

	Pedestrian	Passenger vehicle	Passenger high-speed
Option 1: Linear increase and linear decrease of T_{off}		x*	
Option 2: Linear increase and exponential decrease of T_{off}	x		
Option 3: Linear increase and decrease to the minimum T_{off}	x*		
Option 4: Exponential increase and linear decrease of T_{off}		x	x*
Option 5: Exponential increase and exponential decrease of T_{off}			
Option 6: Exponential increase and decrease to minimum T_{off}	x		

Finally, for a user on a high-speed vehicle, in the first approach we assume that the time within the cell range is quite small and thus the inactive duration time should not be greatly affected. In the second approach, we assume, as before, that although the cell will ask for the user to be transferred to a neighboring cell, it will soon need to be serve by the first cell, and thus the respective cell should be inactive for the minimum possible time. Therefore, we notice that, depending on the degree of overlap between neighboring cells, the cell deactivation process might be implemented with a different design option for the same class of user mobility. The results of the above approaches, i.e. collaboration or not between the cells, are presented in Tables 4 (assuming cell coordination) and 5 (not assuming cell coordination), respectively.

Table 5: Comparative analysis for different user mobility models assuming coordination between neighboring cells

	Pedestrian	Passenger vehicle	Passenger high-speed
Option 1: Linear increase and linear decrease of T_{off}			
Option 2: Linear increase and exponential decrease of T_{off}		x	
Option 3: Linear increase and decrease to the minimum T_{off}			x*
Option 4: Exponential increase and linear decrease of T_{off}	x*		
Option 5: Exponential increase and exponential decrease of T_{off}	x	x*	
Option 6: Exponential increase and decrease to minimum T_{off}			

VI. CONCLUSION

In this paper, we have treated the problem of dynamic cell deactivation in femtocell overlaid LTE-Advanced networks. Firstly, we have provided a detailed categorization of the different energy saving approaches that already exist in current literature, including component-level and system-level energy saving approaches. For each one of the two categories we have further provided a sub-categorization based on the criteria used to save energy in the LTE-Advanced femtocell network. Accordingly, we have formulated and discussed in detail the problems of discontinuous reception at the mobile devices and dynamic cell deactivation of femtocells in LTE-Advanced networks. Then, having as an example the operation of DRX on mobile devices, we proposed design options for dynamic cell deactivation to save more energy on the network. These options involve changing the idle time of the femtocell base station in the following ways a) linear increase and linear decrease of the switch-off time, b) linear increase and exponential decrease of the switch-off time, c) linear increase and decrease to the minimum of the switch-off time, d) exponential increase and linear decrease of the switch-off time, e) exponential increase and exponential decrease of the switch-off time and f) exponential increase and decrease to the minimum of the switch-off time.

Finally, we evaluated these options based on the following factors: a) the network load on the cell; b) the user traffic type used by the users; and c) the mobility of the users in the cell. For each of the above, depending on the subcategories which we include, we have concluded to the following.

Referring to the network load on the cell, when the load on the cell is high, we recommend selecting a linear increase and decrease to the minimum of inactive time. When the user load is medium, we recommend the option of linear increase and exponential reduction of inactive time. When the user load is low, we recommend the option of exponential growth and linear decrease of inactive time.

Referring to the type of the user traffic, when the user is chatting via VoIP, we suggest the option of increasing linearly and exponentially reducing inactive time. When the user browses the Internet, we recommend the option of exponential growth and linear decrease of inactive time. When the user is playing online games, we recommend selecting a linear increase and decrease to the minimum of inactive time.

Referring to the user mobility model (mainly based on the user speed), when the user is pedestrian and there is no cooperation between neighboring cells, we recommend choosing a linear increase and decrease to the minimum of inactive time. When the user is pedestrian and there is cooperation between neighboring cells, we recommend the choice of exponential growth and linear decrease of the inactive time. When the user enters a vehicle and there is no cooperation between neighboring cells, we recommend the option of linear increase and linear decrease of inactive time. When the user enters a vehicle and there is cooperation between neighboring cells, we recommend the option of exponential growth and exponential reduction of inactive time. When the user enters a high speed vehicle and there is no cooperation between neighboring cells, we recommend the option of exponential increase and linear decrease of inactive time. When the user enters a high-speed vehicle and there is cooperation between neighboring cells, we recommend selecting a linear increase and decrease to the minimum of inactive time.

In future work, we plan to study the performance of proposed dynamic cell deactivation mechanisms using system level simulations or mathematical analysis tools.

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