

**Limits on Secondary Transmissions Operating in Uplink Frequencies in Cellular  
CDMA Networks**

by

**Hena Maloku**

Bachelor of Science in Electrical Engineering-Telecommunication, University of Prishtina, 2008

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This thesis was presented

by

Hena Maloku

It was defended on

August 9, 2011

and approved by

Martin Weiss, PhD, Associate Dean & Associate Professor

Prashant Krishnamurthy, PhD, Associate Professor

David Tipper, PhD, Telecommunications Program Chair & Associate Professor

Thesis Advisor: Martin Weiss, PhD, Associate Dean & Associate Professor

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# **LIMITS ON SECONDARY TRANSMISSIONS OPERATING IN UPLINK FREQUENCIES IN CELLULAR CDMA NETWORKS**

Hena Maloku, MST

University of Pittsburgh, 2011

It is well known that electromagnetic radio spectrum is very expensive. This spectrum is managed by government agencies which divides it into frequency bands and then allocates bands to different types of services such as TV broadcasting, cellular telephony ,military usage etc. Lately, the increasing number of wireless technologies and rapid increase in the number of users in cellular telephony highlighted the emerging shortage in the allocated spectrum. From measurements, it has been shown that a major cause of this shortage is inefficient use of spectrum. Many services are active, but they do not have a 100% duty cycle, thus systems are often not operating at full capacity much of the time, which creates a gap in spectrum usage. Thus, the idea of secondary user transmissions has been developed. A secondary user is a non-licensed user which uses licensed spectrum when it is unoccupied by the primary user (i.e., the license holder). These secondary transmissions can happen only as long as the interference caused by them does not harm the primary users by decreasing their quality of service (QoS) or in the worst case scenario by denying them access.

The focus of this dissertation is on better usage of the uplink frequency bands of cellular CDMA networks. We calculate the number of secondary transmissions possible in the cell radius whenever the cell is not operating at full capacity. Further, we explore the possibilities and limitations that such secondary users face in that cell, always keeping in mind the

interference that will be caused to primary transmissions (at the Base transceiver subsystem-BTS) must be less than the threshold that is required to maintain adequate quality of service. We employ simple analysis and we have performed simulations to calculate the dependence of the number of secondary users based on the number of active primary users and also to calculate the interference on the secondary users to evaluate the possibilities and potential for secondary user applications.

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## **PREFACE**

I would like to use this opportunity to express my gratitude to my advisor Dr. Martin Weiss, and to Dr. Prashant Krishnamurthy and Dr. David Tipper for all their help and encouragement throughout the progress of this thesis and also for all their support during my studies.

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## 1.0 INTRODUCTION

The rapid development and deployment of Wi-Fi technology and also the increasing number of users in mobile telephony has resulted in demand for more frequency bands. Due to spectrum scarcity or perhaps also due to the inefficient usage of frequency spectrum, this has become an issue of significant importance, both socially and technologically [1]. One approach to resolving this problem is to find a way for other transmitters to use these existing licensed frequency bands without harming the incumbent licensed users. The question then becomes how the unlicensed secondary user will be able to transmit and with what power in order to meet its requirements but still leave unchanged the QoS of primary users.

To improve the situation of spectrum scarcity, both policy reforms and technological advances are required. Some policy reforms are on the way, such as the FCC's (Federal Communications Commission) ruling in United States to permit unlicensed devices to use underutilized licensed spectrum [2]. From a technological perspective, a lot of research is focusing on cognitive radios, as a potential new technology that will alleviate the problem of spectrum scarcity [3].

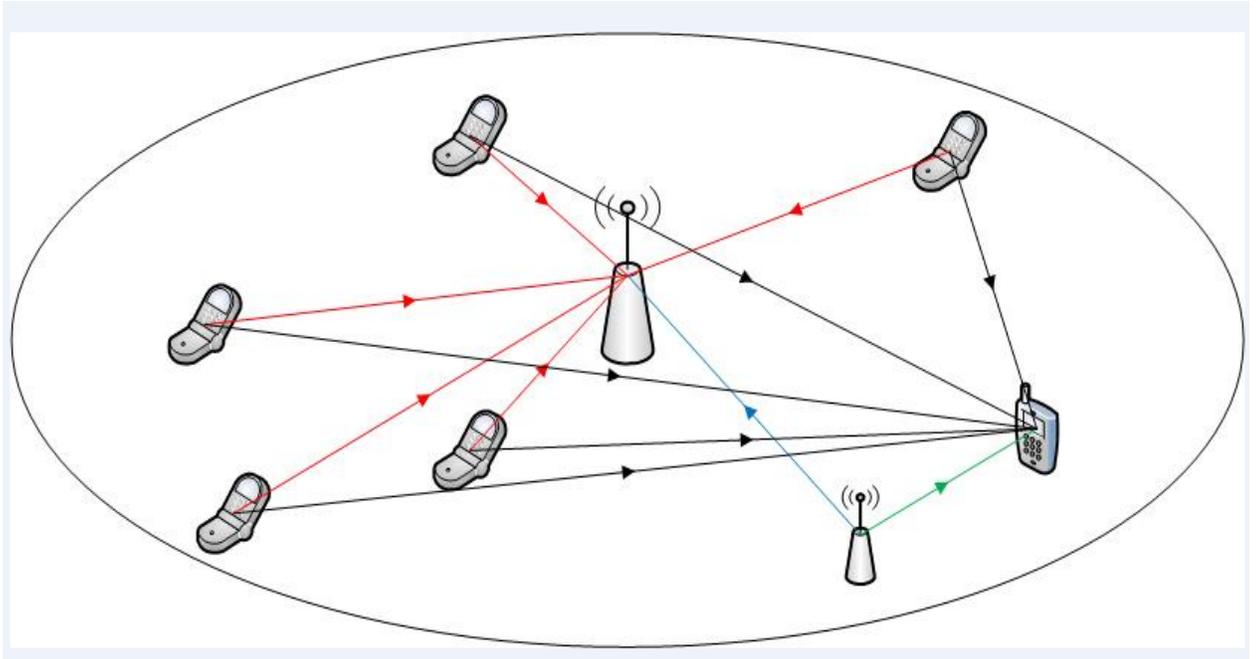
Cognitive radio is a new type of wireless communication, where the wireless devices are able to successfully sense the spectrum, identify unoccupied frequencies and then switch to those frequencies for communication with other devices. In this way, the cognitive radio offers a novel

solution to the underutilization of the spectrum by enabling unlicensed wireless devices to efficiently use vacated frequencies when not used by their legal “owners” [3].

The unoccupied chunks of frequencies within bands of spectrum controlled by licensed users (that we will from now on refer to as primary users) are commonly known as white spaces or spectrum holes. Cognitive radio devices are able to identify these white spaces and use them, for the time duration they are not occupied by the primary user. The devices are also able to detect the appearance of the primary user and promptly vacate the channel. This way, the primary user is still guaranteed an interference-free transmission.

One of the main parameters of cognitive radios is transmission power. The benefit of considering the transmit power is that this power can be changed or reconfigured as long as it's within the legal constraints of the license and the technological constraints of the secondary device. This is possible due to power control. This means that whenever there is no need for a high transmitted power the transmitted power from cognitive radio can decrease in order to reduce the unnecessary interference and also allow additional secondary transmission. Cognitive radios or secondary transmissions can occur in licensed bands as well as in unlicensed bands.

An example architecture of how licensed spectrum sharing is possible (in which this work is focused) is shown in the figure below:



**Figure 1.** Secondary user in a licensed band

In Figure 1, we can see the primary base station and its primary users. Secondary opportunistic users are also placed in the radius of this cell using the same frequency and same technology as the primary system. The secondary base-station will communicate with its secondary users, thus creating interference on the uplink band of the primary system. The main challenge for secondary users existing in the licensed band is their ability of detecting primary users. This is because the capacity available to secondary users depends on the interference coming from primary users and the interference they can cause to primary users. Thus the most important issue in this architecture is interference avoidance with primary user.

Due to this, the secondary transmitter has to be careful of its transmitted power and also to maintain the allowed distance between itself and BTS in order to not produce cause high interference level in BTS and also to maintain a significant distance between itself and primary users.

A similar architecture is used in our work where we explored the CDMA uplink band and opportunities that a secondary user has, as well as the limitations faced by the secondary user. We also assumed that a secondary user uses the licensed spectrum and even in our case the avoidance of interference with the primary user is the most important factor because based on the fact that the secondary user's possibilities are known. In [1] [6], researchers assumed that secondary users were sensing the spectrum and using a technique called spectrum handoff, so that if a secondary user senses that primary user is operating in that band, the secondary user has to immediately vacate the band. That's not the situation in this work when the secondary user doesn't use sensing to decide upon its transmission since we assume that the secondary user a priori knows all the information necessary for successful transmission.

## 2.0 RELATED WORK

In the future it is expected that demand for wireless services will continue to increase thus creating the necessity for more capacity and more availability of spectrum. It has been shown from measurement studies that the lack of spectrum is more because of poor spectrum management than it is really from the lack of availability of frequency bands.

A good solution to address the inefficient usage of spectrum may be the development of equipment that can detect holes in the spectrum and then adjust their transmission characteristics in order to be able to exploit these holes in the spectrum. There are different sensing techniques used for detecting spectrum holes. These techniques are broadly divided into cooperative and non-cooperative techniques. Traditionally most of the research has focused on the accurate detection of primary user transmitters, but there are also techniques that focus on primary user receiver detection. In the non-cooperative mode, each cognitive radio device tries to detect the primary signal based solely on its own local observations. In cooperative techniques, a decision is made taking into account all local observations of all cognitive radio devices in the network

Some of the techniques used for spectrum sensing are:

A Energy Detection

B. Using a Matched Filter

C. Feature Detection

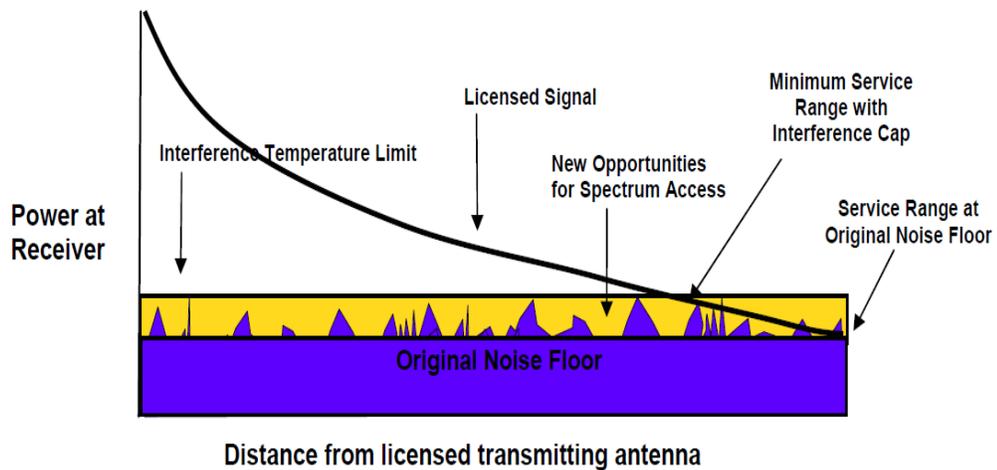
The evidence that there is change in spectrum management can already be seen in the development of the IEEE 802.22 cognitive radio based standard. This is standard used for fixed, point-to-multipoint communications and also for wireless area networks that operate on unused channels in the TV VHF/UHF bands between 54 and 862 MHz on a non-interfering basis [4]. Opportunistic radio-OR (we call this a secondary user) is a radio that is capable of detecting the spectrum holes and using unoccupied frequencies of spectrum.

Given the fact that in many European countries that have implemented UMTS, spectrum has become a luxury, spectrum sharing and its opportunistic use has raised the interest of many. The UMTS FDD channel has separate uplink and downlink bands. Because internet applications have traffic that is asymmetric due to higher downloading data compared to low uploaded data, we can say that uplink bands of spectrum are underutilized [4]. It should be noted that potential opportunities for exploiting the uplink spectrum have to be perhaps consistent with the interference temperature metric proposed by the FCC's Spectrum Policy Force Task. The ITemp threshold is the maximum amount of new interference that a primary receiver could tolerate. This means that this interference metric has to deal with thresholds of interference in a receiver which would enable the primary operator to be able to provide services as usual even though the operator is allowing the use of spectrum by secondary users. All this will be possible only if the threshold of interference is not crossed due to transmissions from secondary users.

The general idea is that everyone can use the spectrum as long as a primary user's QoS requirements are still met. This means that iTemp can be increased when the interference is still under the acceptable limits. But secondary users have to be smart to decrease this iTemp when the interference limit is crossed in order to not decrease the QoS of primary users.[5]. For this

reason iTemp thresholds of different wireless systems that operate in different frequencies are being set up. So for a new transmitter to operate in a frequency band in a certain location, it first has to make sure that when its transmitting power adds to the noise floor that already exists, it still doesn't cross the iTemp threshold and the iTemp limit is not crossed. Noise floor is the noise (interference) which a primary user experiences where there are no secondary users in the system.

In Figure 2 below we present the iTemp concept [5]. The transmission temperature which presents available spectrum opportunities is shown by the space between the interference limit and the noise floor.



**Figure 2.** Interference Temperature metric

There are different models used for investigating better usage of spectrum. We describe some very briefly in the following.

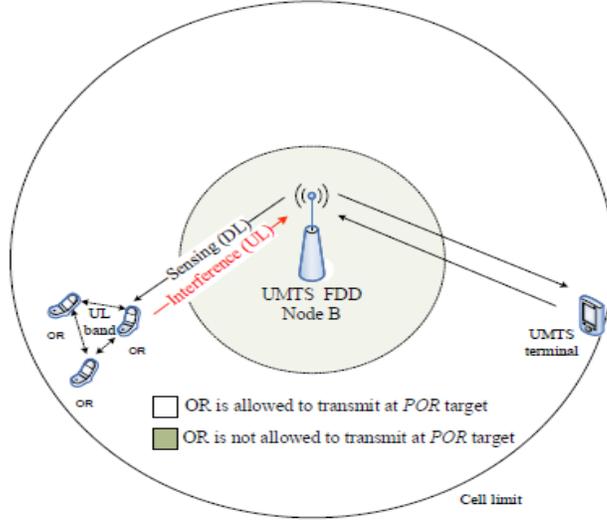
There are models that calculate the opportunistic use of a spectrum band looking at the maximum power limitations, E/I (energy/Interference) thresholds and those that consider outage/capacity probability.

Different scenarios have been considered investigating better usage of downlink and uplink bands of cellular systems. Even though the downlink has been widely explored, there is not much work that exists on the opportunistic use of uplink bands.

Some of the work done over the uplink and described below uses an architecture exploring the opportunistic use of spectrum by secondary users. They are also focused on CDMA networks and their main concern is the degradation of performance of the primary system in terms of the interference level. They also assume only one secondary user sharing the spectrum. In [6], some work has been done by implementing nodes of opportunistic radios such that they will be able to sense the path-loss between themselves and Base Transceiver Subsystem (BTS) of the primary system. Thus by knowing the path-loss, an opportunistic radio can set the transmit power such that it will not produce harmful interference for uplink bands.

However, in CDMA, all users transmit at the same time over the entire bandwidth of a carrier, typically using different spreading codes. In order for the opportunistic radio to transmit it has to be able to sense the unused codes. This is very difficult because the synchronization between opportunistic signals and UMTS signals is hard to achieve at all-times especially if we assume that there is no cooperation among them [7].

One way to solve the problem, presented in [6], is that a certain value of extra interference caused from the opportunistic network is simply added to the available interference. We describe this work below.



**Figure 3.** OR operating in a licensed UMTS uplink band [6]

In Figure 3, we see that there is one opportunistic network with  $M$  nodes, which are operating in the UMTS cell. Here the opportunistic radio (OR) network is the secondary user, who has to compute the maximum allowable power transmitted in order to not degrade the performance for UMTS users. In the white area, secondary nodes are allowed transmissions, but in the grey area, they are forbidden to due to the fact that they are at a very close distance to the BTS. They are forbidden because transmitting with the power that they will need to meet their requirements and being so close to the BTS will result in interference at the BTS.

The maximum power allowed is computed by taking into consideration the total interference:

$$10 \log \left( \sum_{k=1}^M 10^{\frac{P_{OR}(k) + G_{OR} + G_{BS} - L_P(k)}{10}} \right) = 10 \log \left( 10^{\frac{Nth + \mu}{10}} - 10^{\frac{Nth}{10}} \right) - \Gamma$$

Where:

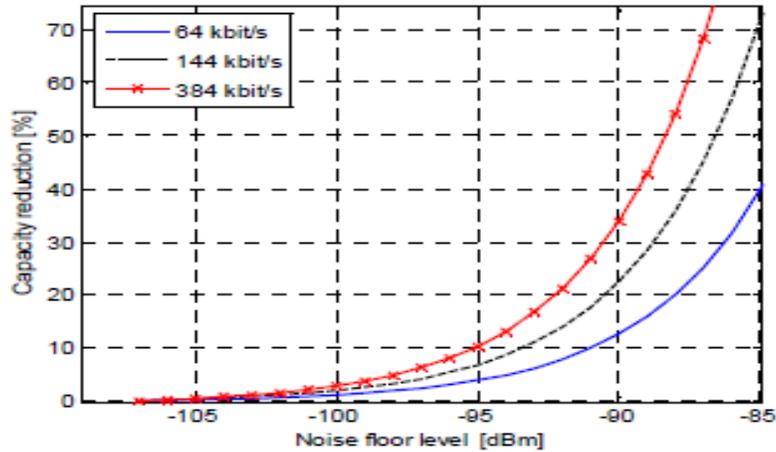
$G_{OR}$  is the antenna gain of the OR,  $G_{BS}$  is antenna gain of the UMTS BTS,  $L_p$  is the estimated path-loss calculated from sensing the medium,  $N_{th}$  is thermal noise floor and  $\mu$  is the extra interference margin that a BTS can support. The factor  $\Gamma$  compensates for shadow fading. We can see from this equation that if  $\mu=0$  that means that there is no transmission opportunity for OR, thus it has to remain silent. The main challenge here is how to set the amount of extra interference that BS can support without decreasing the system performance. For this there are two parameters that we have to check: the capacity of system and the coverage of the system.

To calculate the capacity of the system, the work used the ratio  $E_b/I$  (Energy per bit/interference level) which assumes perfect power control in the UMTS uplink and is given by:

$$\frac{E_b}{I} = \frac{SF * P}{(1 - \beta)(K - 1)P + I_{inter-cell} + N_{th}}$$

The maximum number of uplink channels is given by:

$$K \leq 1 + \frac{SF}{\gamma(1 - \beta)} - \frac{I_{inter-cell} + N_{th} + \mu}{P(1 - \beta)}$$



**Figure 4.** Reduction of uplink cell capacity due to noise floor rise [6]

From Figure 4, we can see the impact that the extra interference has on the system capacity. We can see that if the noise floor rises only by  $\mu=1\text{dB}$ , it causes obvious degradation of the capacity.

The extra interference also causes degradation of the coverage. This because if the interference level was increased by  $\mu$  and there is a mobile station at the edge of the cell which has already reached the maximum allowable transmit power, it cannot increase its power further. The increase in power received at the BTS in order to overcome the interference will require a decrease of the distance that the mobile can be from the BTS. This means that the coverage of the cell will decrease. The path-loss sensing done in [6] is an estimate of the path-loss based on the downlink signals. So they use an algorithm where by capturing the downlink signals and calculating the power received in their receiver, they estimate the path-loss between the BTS and the sensing nodes. We need to point out that this is not very accurate because the characteristics of the downlink and the uplink are not the same.

This is the main difference between this work and our work since we will not use any sensing algorithm to estimate the path-loss. We will assume that all the information required for transmission is already known to the secondary users, either by communication from the BTS or otherwise.

Another work in [1] focused on allowing the secondary user to transmit when the primary signal is so strong that the interference caused by the secondary transmission will not be harmful. As in [6], they assume one secondary user and assume perfect power control in the BTS such that the value of  $E_b/I_o$  in the receiver has to be fixed. They approach to the problem in a different way as follows.

The authors of [1] try to show the extent and possibilities for a secondary user based on the type of spectrum sharing that is used. The key point for secondary transmissions to occur is if the secondary user can know the maximum allowed interference (called STIL) that the BTS can support. By knowing the STIL, a secondary user can determine if sharing is allowed or not. As we mentioned earlier, in cooperative sharing the secondary device knows from communications with the primary network as to how much extra interference it can generate. Even though this requires that the same protocol be supported by both sides, this value of STIL is the close to the real amount of interference that a BTS can support.. On the other hand, in coexistent spectrum sharing there is no communication between secondary and primary networks. So a secondary will have to estimate the amount of interference that it can generate without producing harmful interference to the BTS by perhaps asking a sensor network which uses signals from the downstream communications of the BTS with primary users to predict the possibilities for upstream communications. Note that this might not always be valid because the characteristics of downlink and uplink are not the same; it might be true only in the case when the difference between frequencies used for uplink are not too far from those used in the downlink.

In our work, as we discussed earlier we assume that we have to deal with cooperative sharing and all parameters and interference level allowed STIL in BTS are already known from secondary.

The value of STIL is derived from the total tolerable interference level (TTIL) that a primary can tolerate, from the background noise and from the intercell interference from other users in other cells.

$$STIL = TTIL - [n_o + I_{intc}]$$

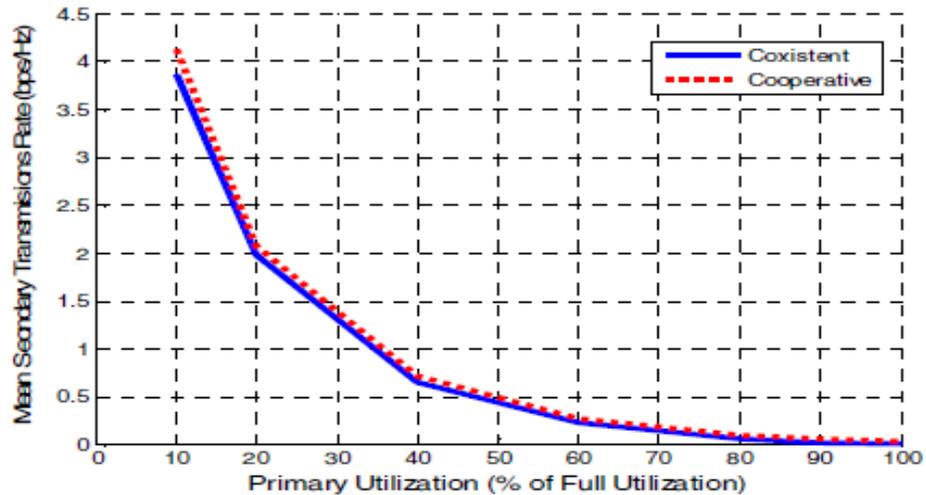
Thus knowing the STIL, a secondary transmitter can determine the maximum transmit power allowed as follows:

$$T_{\max}^S = STIL / L_{B,S} \quad \text{where } L_{B,S} \text{ is calculated from the path-loss between the secondary transmitter and the BTS.}$$

But just knowing the STIL level is not enough because this allowed limit sometimes can be exceeded. This because secondary devices can transmit at a power level that will not cause interference but this will also increase the level of power transmitted by primary users resulting in an increase of interference and decrease of data rates for secondary transmissions.

The authors also considered the data rates that secondary user can achieve while sharing the spectrum. When the utilization of the system is low, (outside the busy hours) a secondary user can obtain good data rates.

But with sharing, they showed that even with a high utilization of the system, a secondary user can still reach modest amounts of communication rates. Also they showed (see Figure 5) below that there is not much difference between cooperative and coexistent sharing in the achievable data rates for a secondary user.



**Figure 5.** Mean secondary Transmission Rate vs. Primary Utilization [1]

Different devices can be used as secondary users. The implementation of femtocells in the macrocell coverage has been considered in order to overcome the demand for high data rates. This implementation of femtocells in macrocells has to be done so that performance of the macro-cell is not impacted. Power control was proposed as a method that can be used for good co-channel operation. The maximum power transmitted was set using the power received from the BTS in the femtocell. In other words even here, downlink measurements were used to calculate maximum power transmitted allowed. This is one example of how spectrum can be shared in the bands where cellular systems operate.

In summary, previous work seems to indicate that using the uplink spectrum may be a feasible approach for secondary users. We investigate this problem in the rest of this thesis under specific assumptions described later.

### 3.0 PROBLEM STATEMENT AND ANALYSIS

The focus of this thesis will be in the secondary use of the uplink spectrum in CDMA cellular telephony and the impact of secondary transmission on primary users. We will focus on Code division multiple Access (CDMA) systems. CDMA system performance depends on the receiver's ability to detect a signal in the presence of interference. There are different parameters such as capacity, coverage and QoS that will determine the performance of the system, but we restrict ourselves to the interference.

Operationally, the capacity of the system is equivalent to how many users can be supported by the system under maximum load. CDMA capacity is different for downlink and uplink, but the system capacity typically depends on the uplink [7]. Thus, the required threshold  $E_b/I_t$  is set on the reverse link. For a CDMA system to have a better performance we need to minimize the interference coming from all users. For this a mechanism called power control is used.

Power control ensures that the received power at the receiver in the BTS coming from different mobiles in the cell will be the same regardless of the mobile's position. It is necessary to control the power because, due to propagation mechanisms, mobiles closer to the BTS would otherwise have larger signal strengths at the BTS compared to the mobiles which are further away [7] leading to the near-far effect.

There are two types of interference to consider. The first is the own-cell interference, which comes from all mobiles which are active on the uplink, and this is the sum of the signal strengths of all powers of such mobiles. Even though the biggest interference comes from primary users, there is a small value of interference added which is usually considered to be additive white Gaussian noise. The other interference comes from neighboring cells. The total interference then will be sum of the total own-cell interference and the other interference factor.

Consider a cell that can support  $M$  active mobiles and assume perfect power control, so that each of these  $M$  mobiles will face an interference coming from  $(M-1)$  interferers. The own-cell interference  $I_o$  in the BTS is given by [8]:

$$I_o = \frac{1}{B_w} \sum_{i=1}^{M-1} v_f S_{ri} = \frac{(M-1)Sv_f}{B_w} \dots\dots\dots(1)$$

Where,

$v_f$  = average reverse link activity factor which can take values from 0.4—0.6

$S_{ri}$  = signal power received from each mobile at BS. This signal power provides the bit energy

$$E_b = \frac{S_{ri}}{R} \dots\dots\dots(2)$$

$R$ =mobile transmission rate (in bps)

$$I_o = (M-1)Sv_f \dots\dots\dots(3)$$

Considering the interference that comes from active mobiles in neighbor cells, which is basically a fraction of total interference that occurs at the receiver.

$$I_{oc} = MfSv_f \dots\dots\dots(4)$$

And  $f$  can take values from 0.56—1.28

Total interference is given by:

$$I_{total} = I_0 + I_{oc} = \frac{[(1+f)(M-1)]Sv_f}{B_w} \dots\dots\dots(5)$$

The threshold in the receiver is given by:

$$\frac{E_b}{I_0} = \frac{B_w}{R} \frac{S}{(1+f)(M-1)V_f S} = \frac{G_p}{(1+f)(M-1)V_f} \dots\dots\dots(6)$$

Considering the interference from a secondary user:

$$\frac{E_b}{I_0} = \frac{G_p S}{(1+f)(M-1)V_f S + f_{sec} S_{sec}} \dots\dots\dots(7)$$

Where,

$f_{sec}$ =interference factor from secondary user (no power control and how long the secondary user may be active)

$S_{sec}$ =power received in BTS from secondary transmission

Considering the imperfect power control factor  $\eta_c$  which can take values from 0.7—0.85, we have:

$$\frac{E_b}{I_0} = \frac{G_p S}{(1+f)(M-1)V_f S \eta_c + f_{sec} S_{sec}} \dots\dots\dots(8)$$

where

$f_{sec} S_{sec}$  - interference caused from secondary user

$S$  - is power received from all primary users in BTS.

Taking into consideration these formulas and other assumptions that we will discuss later, we will try to find important parameters of the system which can determine possibilities and limitations that a secondary user will face when it operates in the area and spectrum band already

used by the primary user. Some of the parameters are: maximum allowed transmitting power of primary user (beyond which the primary mobile cannot increase its transmit power), transmit power limits of secondary user, the minimum distance that the secondary transmitter can be from the BTS in order to not cause an increase in interference, and the maximum distance between secondary transmitter and secondary receiver that will allow the secondary application's requirement's to be fulfilled.

### **Assumptions:**

For our simulations, we assumed cooperative sharing of spectrum where the secondary users know some of the parameters of the BTS. We also assumed the following parameters:

- a cell of a CDMA network with radius of the cell is  $R=8$  km
- two different models of path loss were used to investigate the influence of path-loss model: Okumura-Hata path-loss model free space path loss model.

**Okumura-Hata Model** is the most commonly used model for propagation losses which predicts the behavior of cellular transmissions. This model is based on empirical measurements. This model can be used if the parameters are within these ranges:

- Frequency: 150 MHz to 1500 MHz
- Mobile Station Antenna Height: between 1 m and 10 m
- Base station Antenna Height: between 30 m and 200 m
- Link distance: between 1 km and 20 km.
- Frequency  $f_c=880$ MHz, antenna height of receiver  $h_m=2$ m, antenna height of BTS transmitter  $h_b=40$ m

The path-loss  $L_p$  is given by:

$$L_p = 69.55 + 26.16 \log_{10}(fc) + (44.9 - 6.55 \log_{10}(h_b)) \log_{10}(d) - 13.821 \log_{10}(h_b) - ah_m$$

Where

$$ah_m = 83.2 [\log_{10}(11.75 \times h_m)]^2 - 4.97 \dots \dots \dots \text{for } fc > 400 \text{ MHz}$$

On the other hand, the **free space path-loss** model is not very realistic because it assumes that transmitter and receiver have a clear line of sight and uses an optimistic attenuation factor with distance. Usual this is not the case in the city and urban areas where the objects between transmitter and receiver in most of the cases are present.

To calculate the path-loss using the free-space model, we use:

$$L_p = P_t(\text{dBm}) - P_r(\text{dBm}) = 21.98 - 20 \log_{10}(\lambda) + 20 \log_{10}(d)$$

$$\lambda = \frac{c}{f} \text{ where } c = \text{speed of light} = 3 \times 10^8 \text{ m/s and } f = \text{frequency}$$

$d$  = the distance between transmitter and receiver

It is known that :

$$L_p = P_t(\text{dBm}) - P_r(\text{dBm})$$

We assume the maximum allowed power transmitted by the primary user is:

$$P_t(\text{MS}) = 24 \text{ dBm}$$

$$\frac{E_b}{I} = 7 \text{ dB}$$

In order to calculate  $I_{sec}$  using equation (8), we assume these parameters:

$$B_w = 5000.Hz$$

$$R = 9.6kbps$$

$$V_f = 0.4$$

$$f = 0.67$$

$$\eta_c = 0.8$$

$M$  (number of supported users) is calculated using equations (1) and (2),

$$M = \frac{G_p}{v_f \left( \frac{E_b}{I_o} \right)} + 1 = 190 \text{ users}$$

Calculating  $I_{sec} = f_{sec} \cdot S_{sec}$  from:

$$\frac{E_b}{I_o} = \frac{G_p S}{(1+f)(M-1)V_f S \eta_c + f_{sec} S_{sec}}$$

We have:

$$I_{sec} = \frac{G_p S}{10^{\left( \frac{E_b}{I} \right) / 10}} - (1+f)(M-1)V_f S \eta_c \dots\dots\dots(9)$$

For different values of  $M=[1:190]$ , we can plot the relation between the maximum interference from secondary transmissions and the number of active users  $M$ .

We will also calculate the interference level at the secondary receiver, which will be a more difficult problem because a secondary user cannot enforce power control on primary users,

so the signals coming from primary users  $M$  of them will be received at different values of received power.

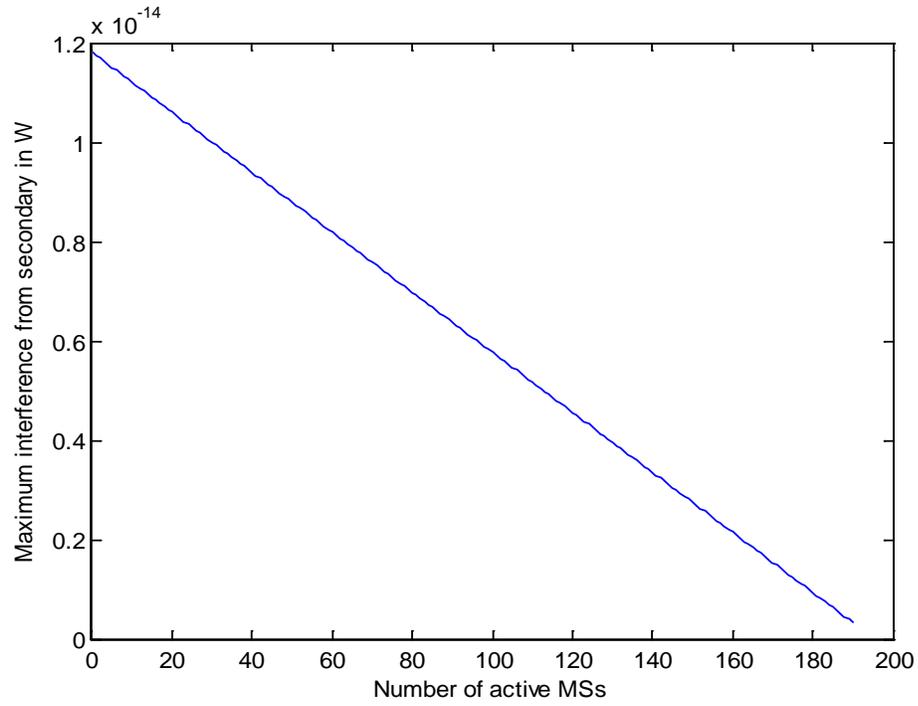
$$\frac{E_b}{I} = \frac{G_p \times P_{r\_sec\_sec}}{\sum_{N=1}^M P_{r\_sec\_ms} (MS) \times (1 + f) \times v_f \times \eta_c}$$

The simulations are done by fixing the position of the secondary transmitter/receiver with respect to the BTS and primary users. During the simulations, the number of primary users is increased gradually with each new primary user generated with a random position (with an equal probability of appearing anywhere in the cell). However this position is maintained during one trial (no mobility is assumed). In total 200 trials are performed for each set of parameters.

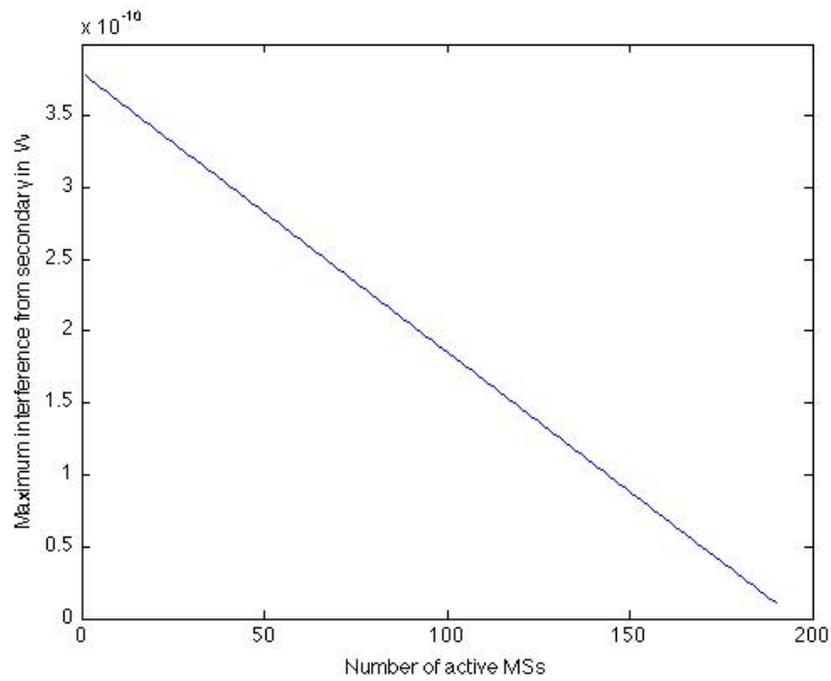
## 4.0 RESULTS AND DISCUSSIONS

In this chapter we, will present the results of the simulation done in order to show the possibilities and opportunities for a secondary user operating in a cell of a cellular CDMA system. We assumed that the secondary network uses the same technology as primary system as described previously. Also we assume different scenarios trying to find the tradeoffs between important parameters such as: minimum allowed distance between BTS and secondary transmitter, maximum allowed distance between secondary transmitter and secondary receiver, and maximum allowed transmission power of secondary transmitter by which secondary limits and possibilities can be set.

I. In Figures 6 and 7, using equation (9), we have plotted the relationship between maximum interference coming from secondary transmitter at a BTS and the number of active primary users  $M$  in the cell. We only consider one cell.



**Figure 6.** Maximum allowed interference from secondary transmitter at the BTS considering Okumura-Hata path-loss model

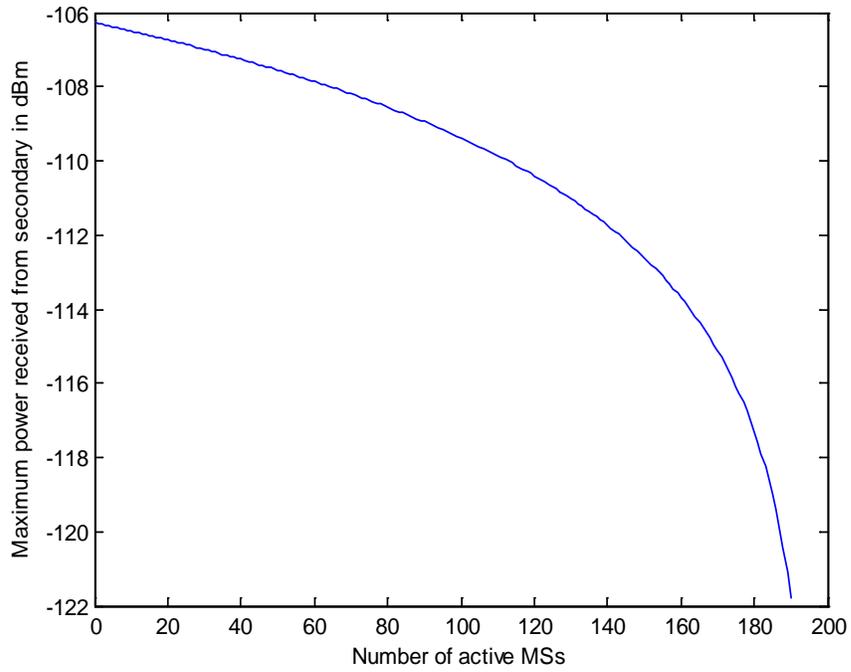


**Figure 7.** Maximum allowed interference from secondary transmitter at the BTS assuming a free space path-loss model

As it was expected, we can see from the plots in Figures 6 and 7 that increasing the number of active users implies that the interference that can be caused from the secondary user drops linearly. This is because the power received from the secondary is linearly dependent on number of active users  $M$ . It is also seen from the two plots that when the path-loss model was changed from Okumura-Hata to free space path-loss model, the allowed maximum interference caused from secondary is higher for same values of  $M$ . Because there is little loss of power from the primary users to the BTS and because the BTS employs power control, the primary users can transmit at much lower power levels, therefore allowing the secondary to transmit at higher power level without causing more interference than allowed.

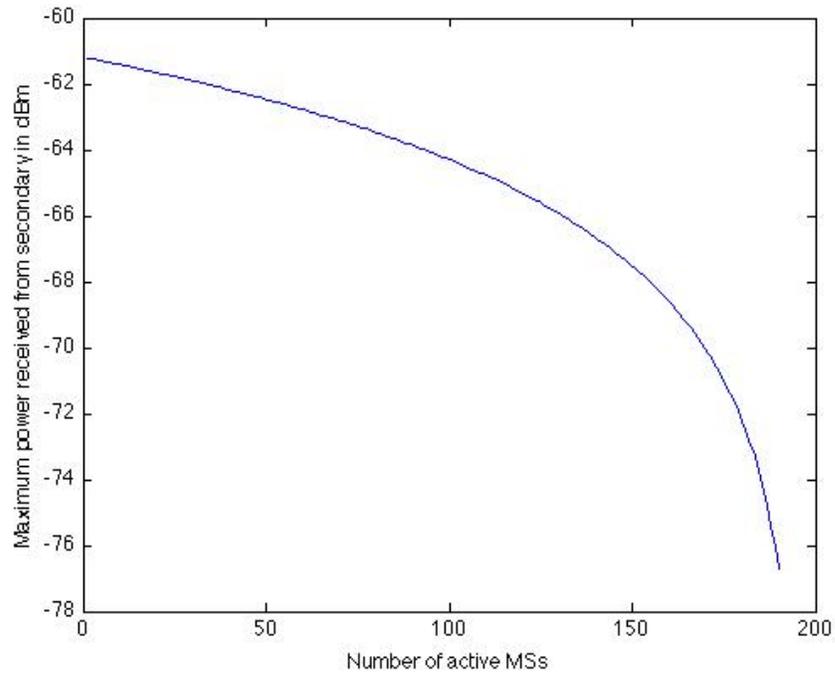
We can calculate the path-loss between a secondary transmitter and BTS for different values of distance  $d$  and see how the power received at the BTS changes depending on the number of active users.

**II.** In Figures 8 and 9 we plotted the maximum power received at the BTS from the secondary transmitter in dBm.



**Figure 8.** Maximum allowed power received from secondary at the BTS versus the number of active MSs

considering Okumura-Hata path-loss model



**Figure 9.** Maximum allowed power received from secondary at the BTS versus the number of active MSs

considering free space path-loss model

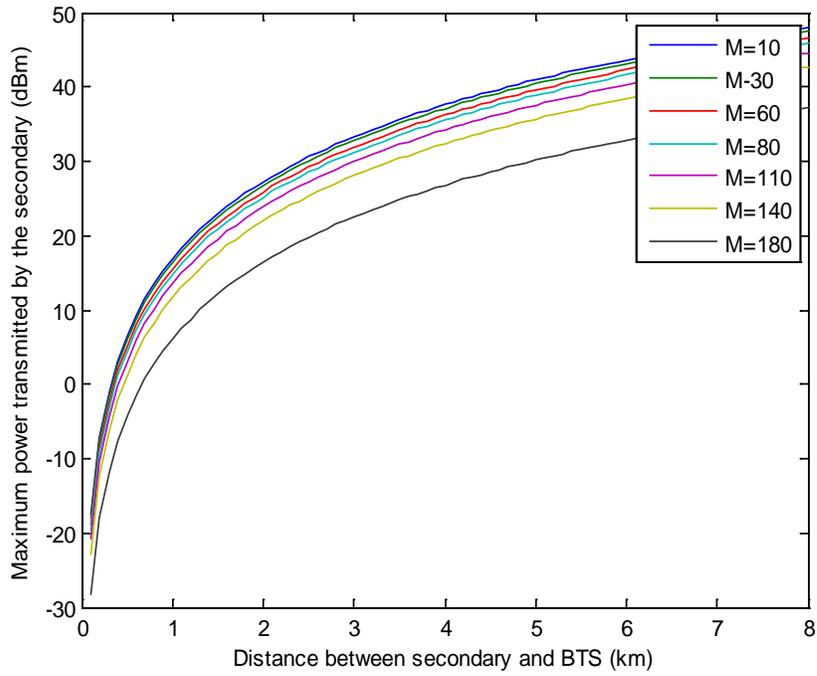
We see from the two plots that the allowable power received from secondary transmitter at the BTS drops rapidly when the number of active users  $M$  approaches the maximum. This means that in the case where in the cell most of the users are active, there is no opportunity for secondary transmissions. This shape of the graph occurs because the power received depends on the path-loss and as we know path-loss depends on distance so it does not have a linear curve.

For the free space path-loss model, the shape of the curve remains the same, however the value of the maximum received power from secondary in BTS is higher for same values of  $M$ , as expected.

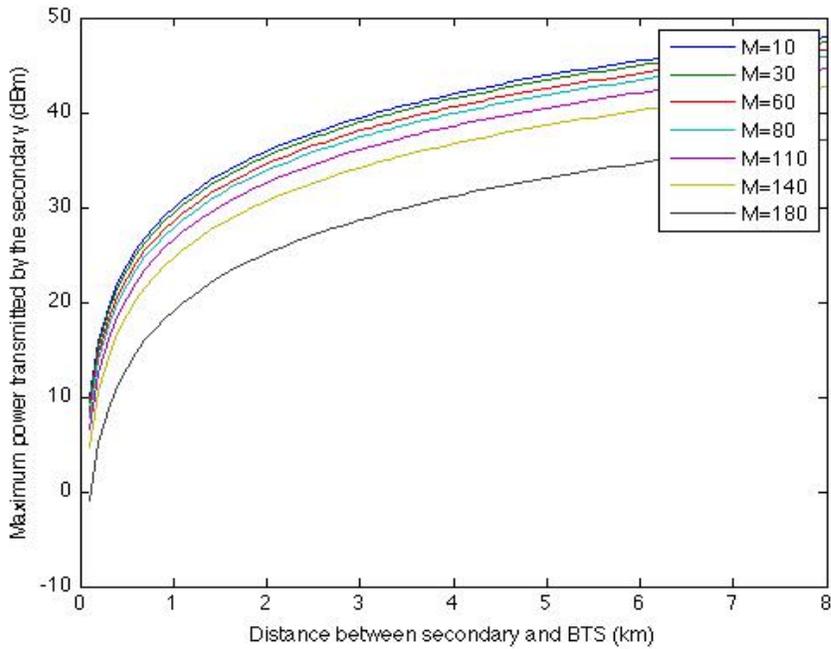
To explore the tradeoffs between power transmitted, distance and number of active users in the cell, we will consider different scenarios.

1. In the first case we can assume that we have fixed number of users  $M$  for different cases, such as:  $M = 10, 30, 60, 80, 110, 140$  and  $180$ .

We will try to show how the transmitting power of secondary user changes with distance by increasing the number of primary users  $M$ .



**Figure 10.** Maximum transmitting power of secondary user versus the distance between the secondary user and the BTS considering Okumura-Hata path-loss model



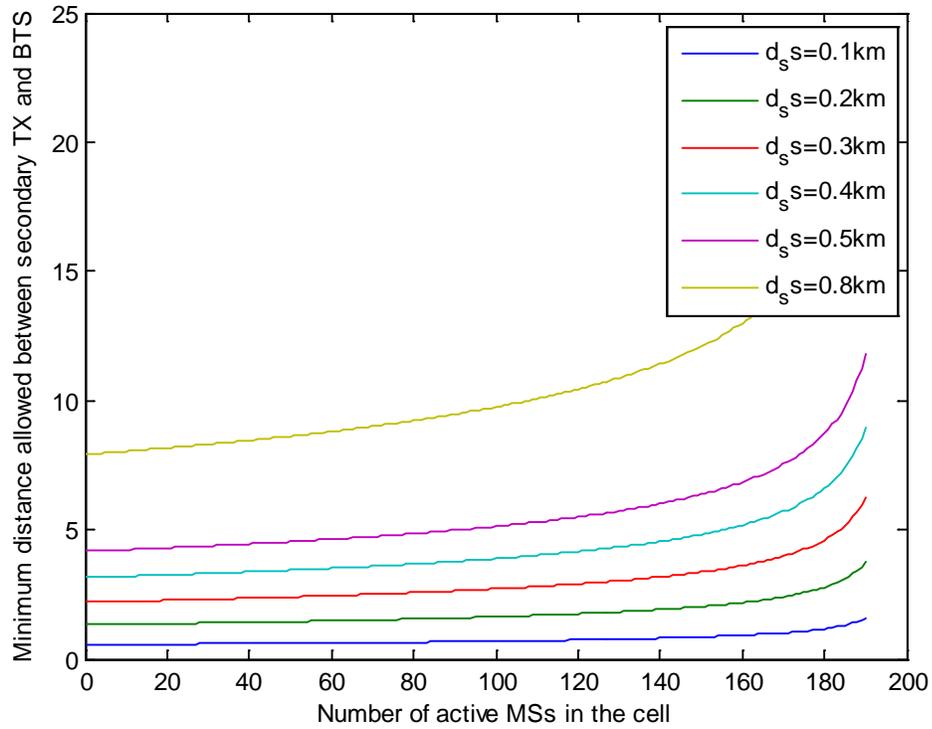
**Figure 11.** Maximum transmitting power of secondary user versus the distance between the secondary user and the BTS considering free space path-loss model

We can see from Figures 10 and 11 that as the distance between the secondary and BTS increases, the maximum allowed transmitted power increases. This is because the farther the secondary transmitter is from the BTS, the smaller is the amount of interference caused by it. But this also depends on the number of primary users that are active in the cell at that time. We can see that in the case where there are only 10 users in the cell, the transmission power of the secondary, even when they are nearby, can be high because the interference caused in the BTS will still be within the limits. But as the number of primary users  $M$  increases, we can see that the allowed transmitted power of the secondary decreases. This is more obvious when the number of primary users  $M$  almost reaches the maximum capacity. This happens because, when  $M=180$ , the interference level acceptable in the BTS has almost reached its limits, so there is no possibility for high transmission power of secondary users, because they would cause high interference, thus creating a performance degradation in the primary network.

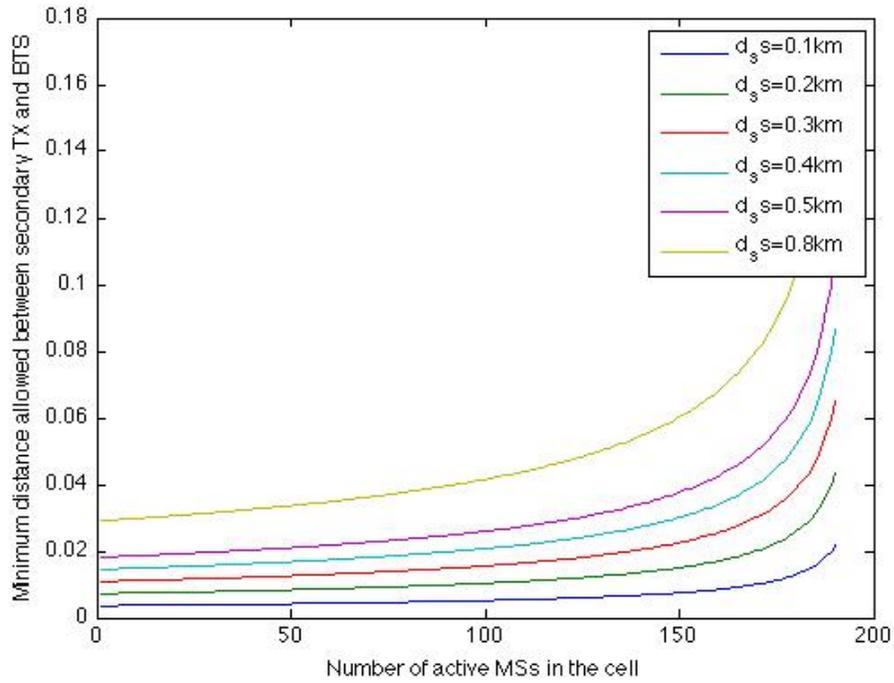
We can also note from the two graphs that the path-loss model only plays a role for smaller distances between the secondary transmitter and the BTS. It can be seen from Figure 11 that for smaller distances in the free-space path-loss model, the power transmitted by the secondary user can be higher than that assuming the Okumura-Hata Model, which is shown in Figure 10, but for larger distances between the secondary user and the BTS, the difference is much smaller.

2. In the second scenario we assumed that we have a fixed distance between the secondary receiver and the secondary transmitter. Putting a threshold in the secondary receiver to be  $P_{r_{sec}} = -90$  dBm and using again the Okumura-Hata model as the path-loss model between the secondary receiver and the secondary transmitter, we can calculate the power transmitted by the secondary transmitter. Then, knowing the power received from the secondary

transmitter at the BTS and using the path-loss model, we can find the minimum distance allowed between the BTS and the secondary that will not cause interference in the BTS to increase more than the permitted minimum.



**Figure 12.** Minimum distance between secondary TX and BTS considering Okumura-Hata path-loss model



**Figure 13.** Minimum distance between secondary TX and BTS considering free space path-loss model

We can see from the plots in Figures 12 and 13 that for small distances between the secondary transmitter and secondary receiver, where there is no need for high transmitting power even if the number of active primary users is high, the distance between the secondary transmitter and the BTS can be small. This is not the case when the distance between secondary transmitter and secondary receiver increases for example  $d_{s-s}=800$  m because this will result in a higher transmission power from the secondary transmitter to achieve good communication reliability, which, being close to BTS is not allowed due to the interference caused.

Also the interference in the secondary receiver was not taken into account in either of these plots which is not the realistic case.

We can see from the plots that the values vary greatly for the two different path-loss models that we have considered. The minimum distance allowed between secondary transmitter and BTS in the free-space path loss model is in the range of hundreds of meters depending on the

number of active MS users and distance between secondary transmitter and receiver, while this distance is in the range of a couple of kilometers for the Okumura-Hata path-loss model .One explanation for this is that the threshold of -90dBm set for the power received at secondary receiver in free-space conditions can be reached very easily with a low transmitting power from secondary transmitter which would not cause a lot of interference to the BTS even in proximity.

3. In the third case we assume that the secondary transmitter has a fixed distance between itself and BTS. This is the same as in the second case where we assumed that the power received at the secondary receiver has to be  $Pr_{sec} = -90$  dBm. See Figures 14 and 15 below.

Here, we are trying to find the maximum distance that the secondary receiver can be from the secondary transmitter in order to meet the requirements of transmission. We should take into consideration the impact of the number of primary users in the cell.

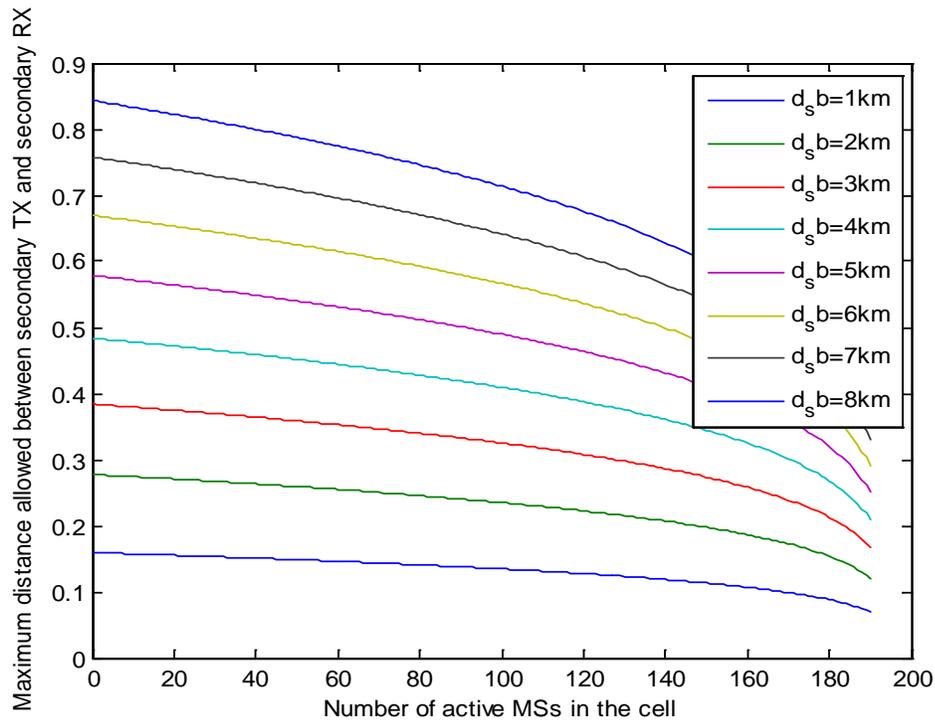
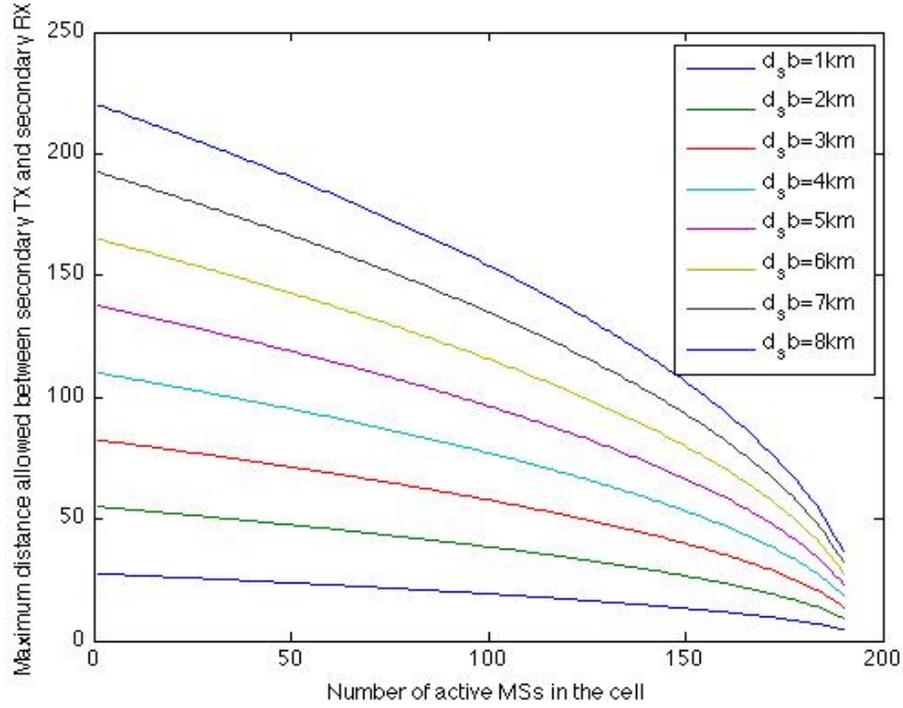


Figure 14. Maximum distance between secondary TX and RX considering Okumura-Hata model



**Figure 15..** Maximum distance between secondary TX and RX considering free space path-loss model

We can see from the plots in Figures 14 and 15 that as far as the secondary transmitter is far from the BTS, the distance between the secondary transmitter and secondary receiver can be higher. This distance will drop fast by increasing the number of active users in the cell.

As in the previous scenario, the values of the maximum distance between the secondary transmitter and receiver differ greatly for the two path-loss models, for similar reasons.

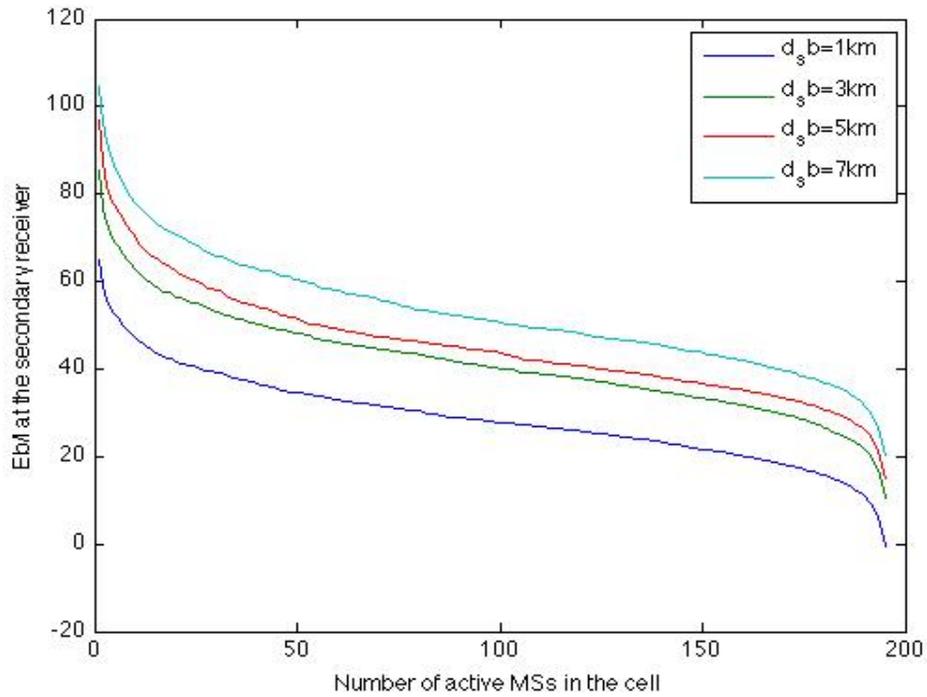
Interference in the secondary receiver was not taken into account again.

4. In the fourth scenario we calculated the threshold of  $E_b/I$  at the secondary receiver without taking into consideration the previous assumption of  $Pr_{sec} = -90$  dBm. To calculate this value, the following formula was used:

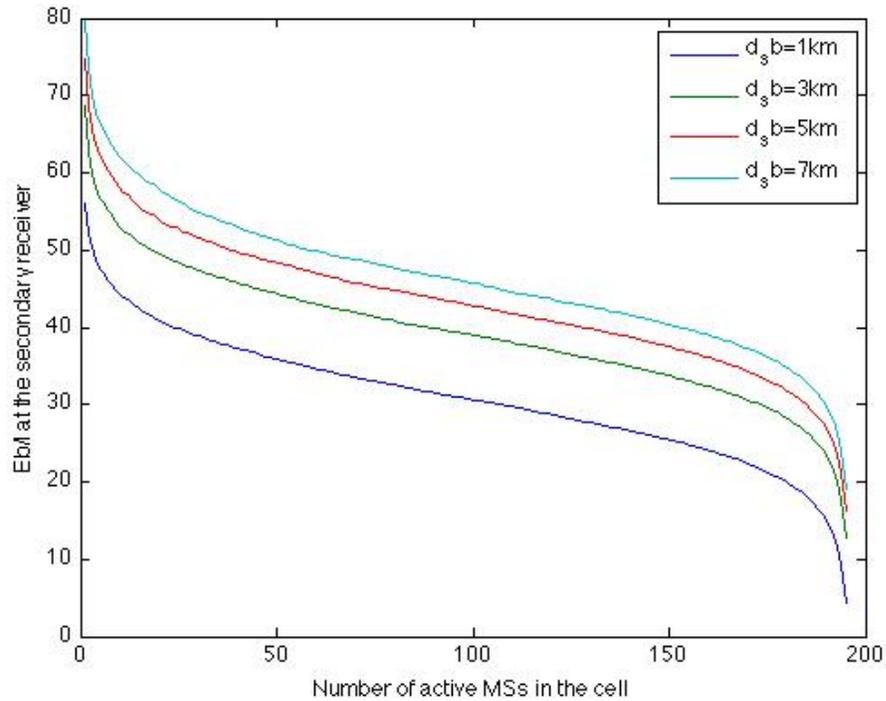
$$\frac{E_b}{I} = \frac{G_p \times P_{r\_sec\_sec}}{\sum_{N=1}^M P_{r\_sec\_ms}(MS) \times (1 + f) \times v_f \times \eta_c}$$

The same values for  $G_p$ ,  $f$ ,  $v_f$  and  $\eta_c$  were used for the secondary and primary because as we mentioned earlier, we are assuming that they use completely the same technology (and we assume the activity as well).

In this case we have fixed the distance between the secondary transmitter and receiver at 800 m and have varied that distance between the BTS and the secondary transmitter from 1 to 8km to get 4 different curves. See Figures 16 and 17.



**Figure 16.**  $E_b/I$  at secondary receiver considering the Okumura-Hata path-loss model

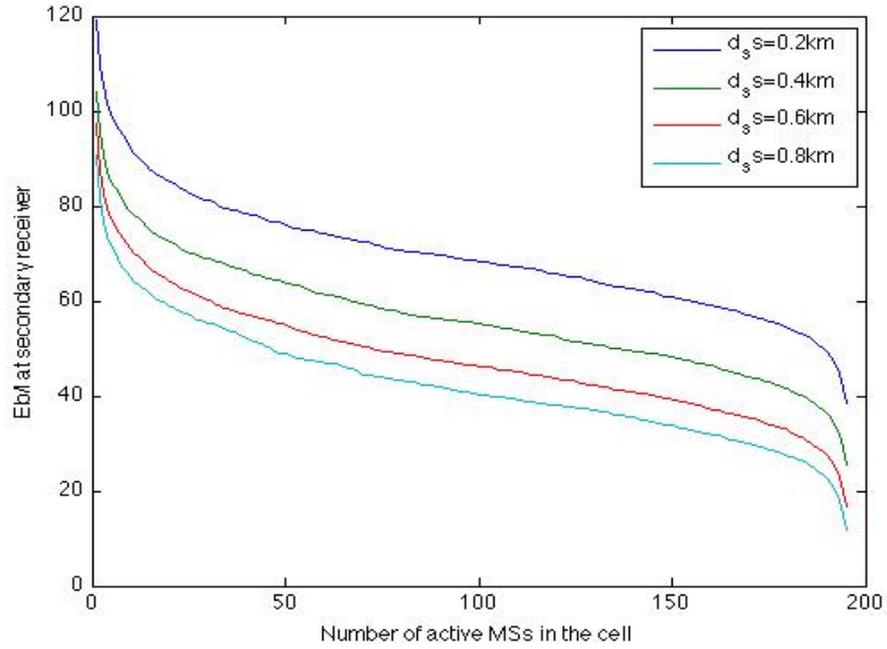


**Figure 17.**  $E_b/I$  at secondary receiver considering the free space path-loss model

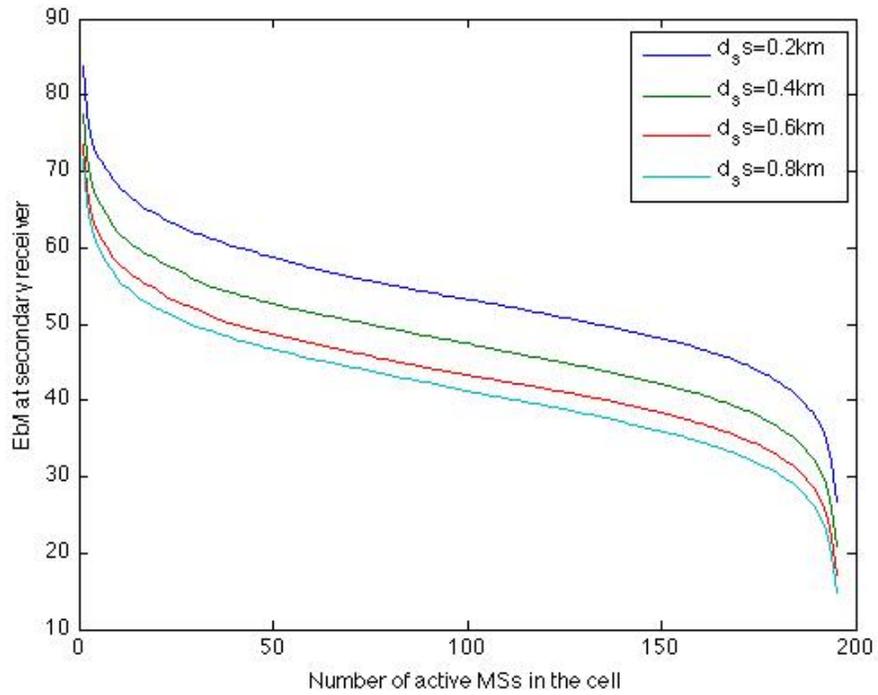
We can see from both Figures 16 and 17 that the value of  $E_b/I$  decreases when the number of users  $M$  increases because the interference coming from primary users will increase which results in decreasing the value of  $E_b/I$ . We can also see from the plots that for the Okumura-Hata path-loss model the values of  $E_b/I$  at the secondary receiver are slightly higher than that for the free space model. One explanation for this is that, for the free space path-loss model, the allowed transmit power of secondary is higher (see Figure 11) and there is little power loss during transmission. Thus, the interference coming from active primary users increases at the same rate.

5. As in the previous case, we are trying to see the tradeoff between the threshold value of  $E_b/I$  and the number of primary users  $M$ . What is different from previous case is that here we have fixed the distance between the secondary transmitter and the BTS at 4 km and then varied

the distance between the secondary transmitter and receiver from 200 to 800m. See Figures 18 and 19.



**Figure 18.**  $E_b/I$  at secondary receiver considering the Okumura-Hata path-loss model



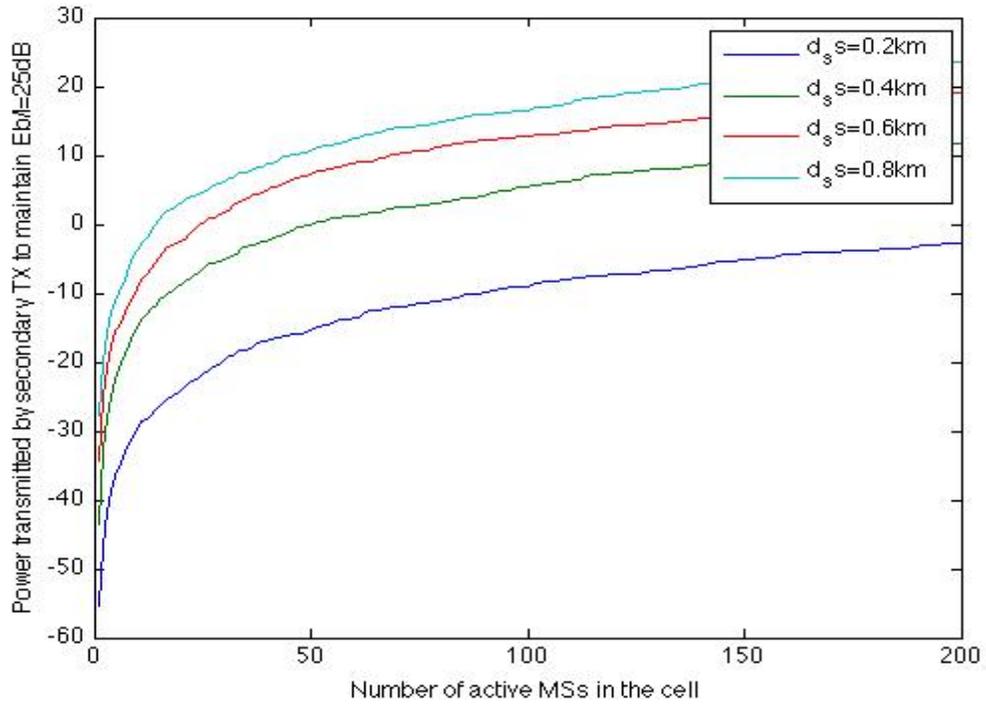
**Figure 19.**  $E_b/I$  at secondary receiver considering the free space path-loss model

We can see from Figures 18 and 19 that as before, the value of  $E_b/I$  decreases when the number of users  $M$  increases because the interference coming from primary users will increase which results in decreasing the value of  $E_b/I$ . As in the previous scenario, for the Okumura-Hata path-loss model the values of  $E_b/I$  at the secondary receiver are slightly higher than that for the free space model.

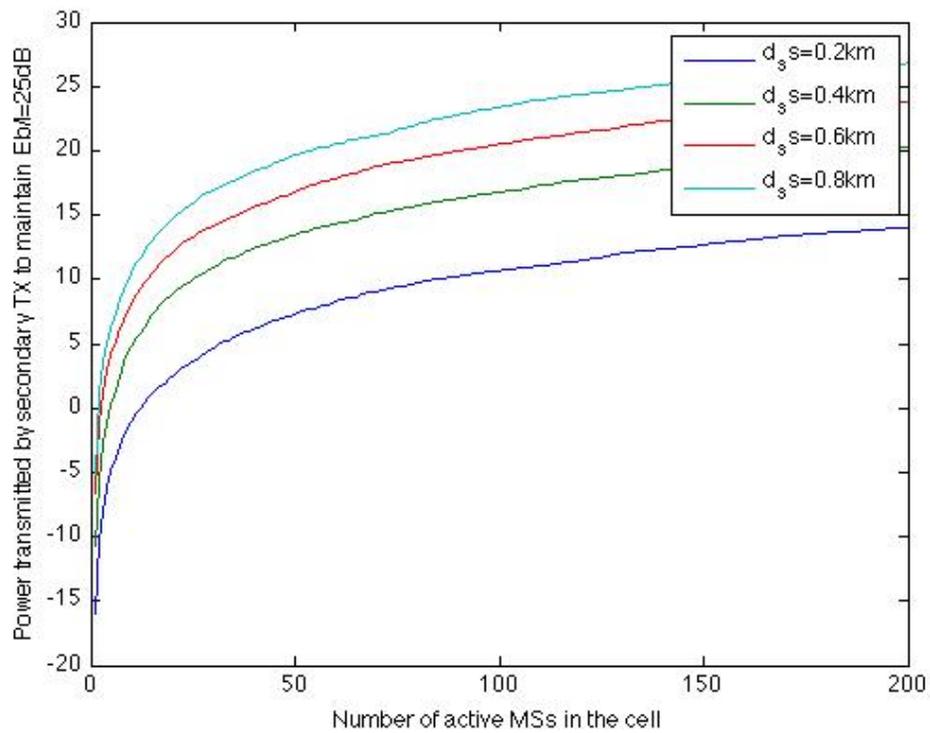
**6a.** In the sixth scenario we assumed a fixed threshold for  $E_b/I$  in secondary receiver. This because setting a threshold on  $E_b/I$  is more reasonable since we can determine the power at which the secondary TX has to transmit. Different  $E_b/I$  values are considered namely, 25 dB, 20 dB, 15 dB and 10 dB

In this case if we fix the distance between the secondary TX and RX we can calculate the minimum power transmitted by the secondary transmitter. The distance between the secondary TX and BTS is fixed at 4 km. See Figures 20 through 27.

$$E_b/I_{sec} = 25 \text{ dB}$$



**Figure 20.** Power transmitted by secondary TX considering Okumura-Hata path-loss model



**Figure 21.** Power transmitted by secondary TX considering free-space path-loss model

$$E_b/I_{sec} = 20 \text{ dB}$$

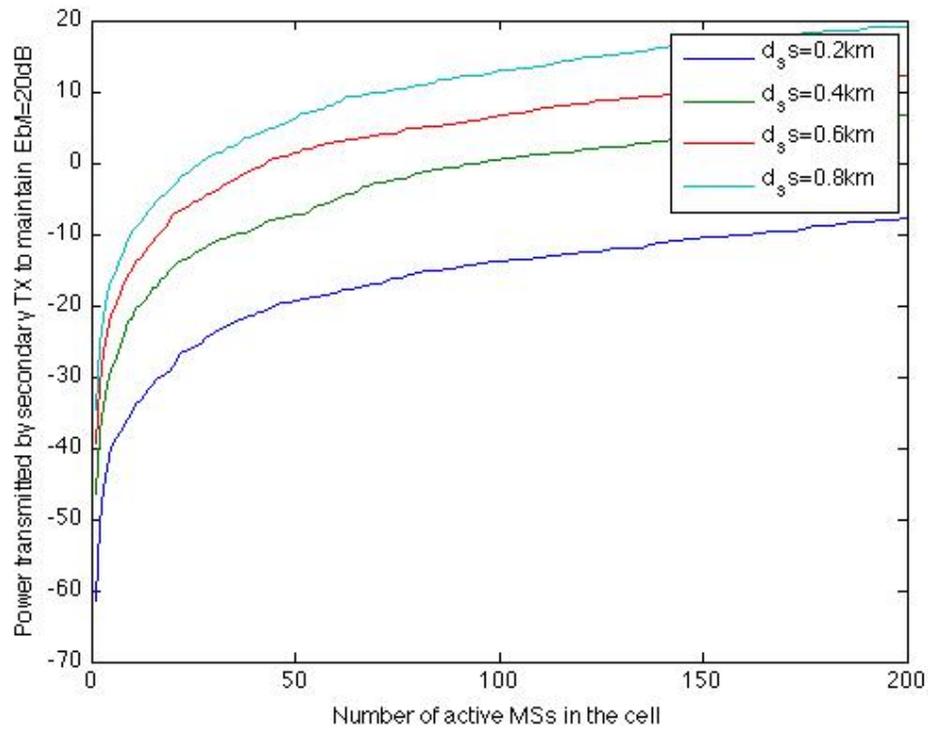


Figure 22. Power transmitted by secondary TX considering Okumura-Hata path-loss model

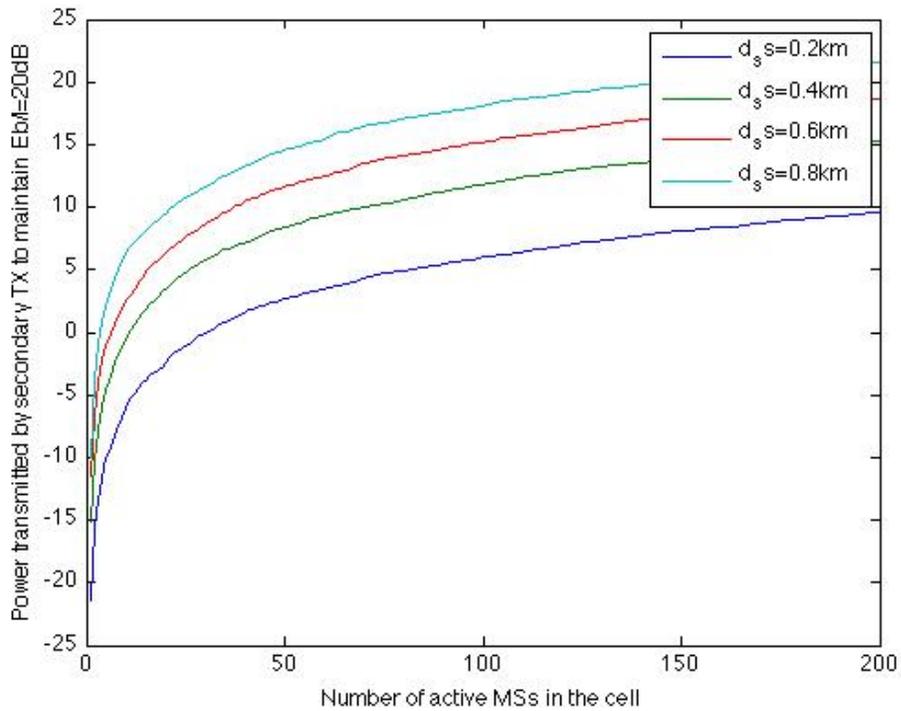
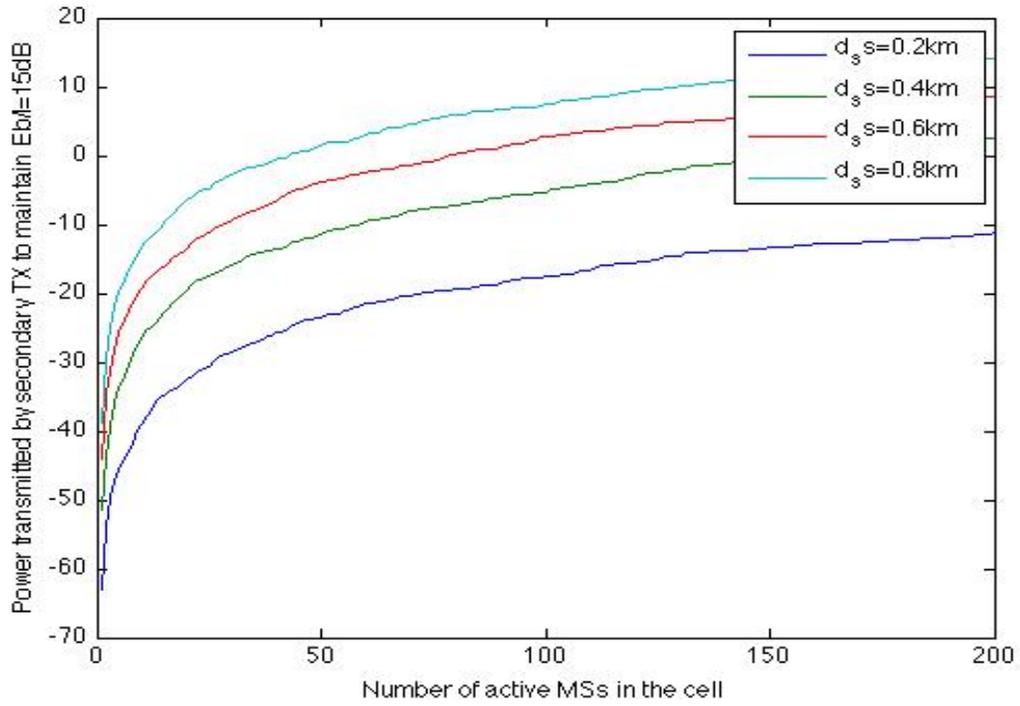
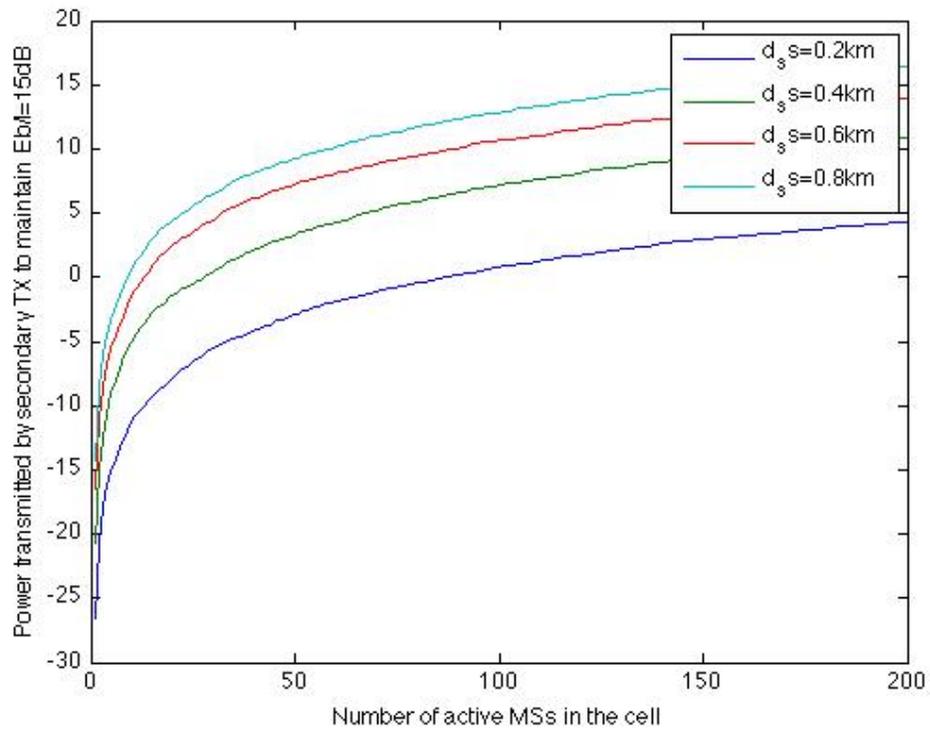


Figure 23. Power transmitted by secondary TX considering free space path-loss model

$$E_b/I_{-sec} = 15 \text{ dB}$$



**Figure 24.** Power transmitted by secondary TX considering Okumura-Hata path-loss model



**Figure 25.** Power transmitted by secondary TX considering free space path-loss model

$E_b/I_{sec}=10\text{dB}$

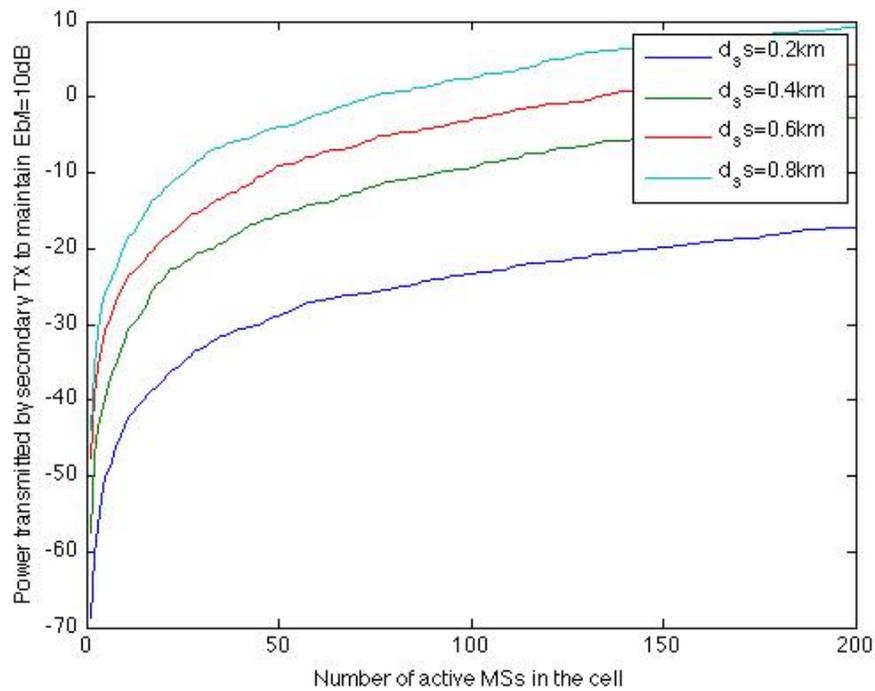


Figure 26. Power transmitted by secondary TX considering Okumura-Hata path-loss model

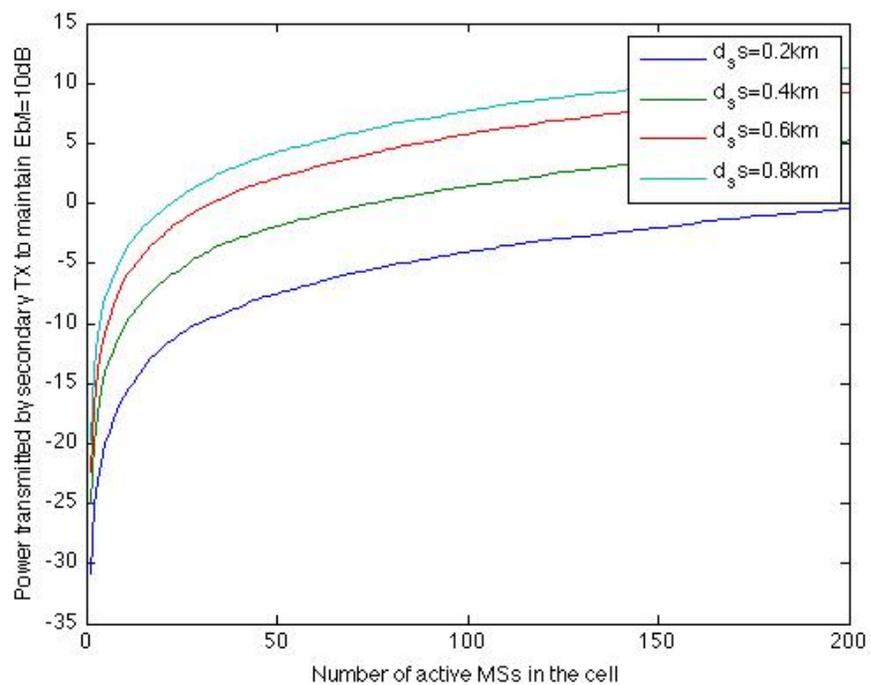


Figure 27. Power transmitted by secondary TX considering free space path-loss model

We can see from the above plots that the smaller the number of active users  $M$  is, the smaller the transmit power of secondary transmitter needs to be. Alternatively, the distance between secondary TX and RX can be increased. Also, as expected, the lower the threshold for  $E_b/I$  at the secondary receiver is set, the smaller the necessary transmitting power of secondary transmitter has to be. Also, as can be seen from the various plots, for the different thresholds, the necessary secondary transmitting power to maintain a certain  $E_b/I$  at the secondary receiver, is higher in the free space path-loss model than in the Okumura-Hata path-loss model. This occurs because although the power loss is small in free space conditions, the interference from active primary users in secondary receivers is also much higher due to the small power loss.

**6b.** For the same case fixing the distance between secondary TX and RX we can calculate how close can secondary TX get to the BTS without causing too much interference depending still on the number of primary users  $M$ . See Figures 28 through 35.

$$E_b/I_{sec} = 25\text{dB}$$

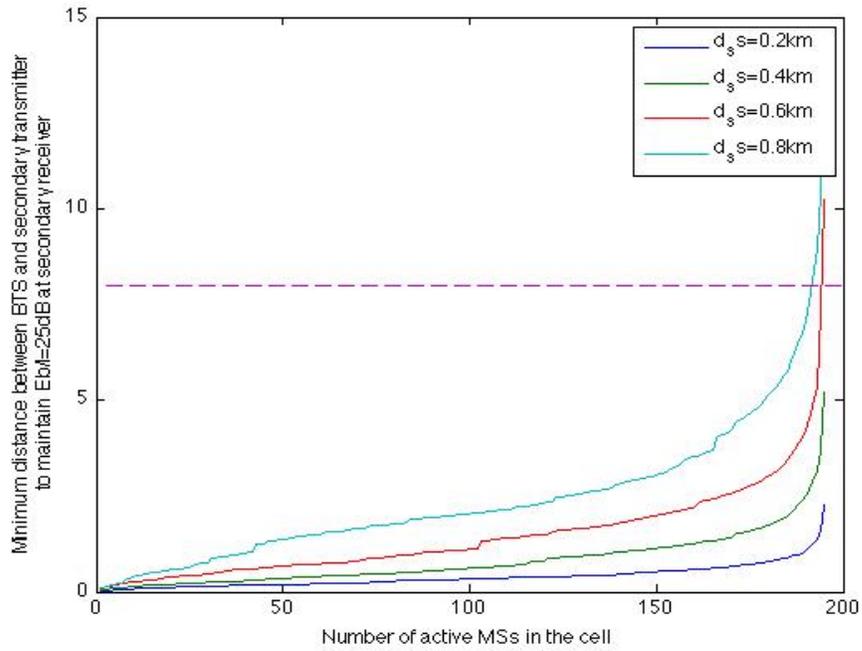


Figure 28. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

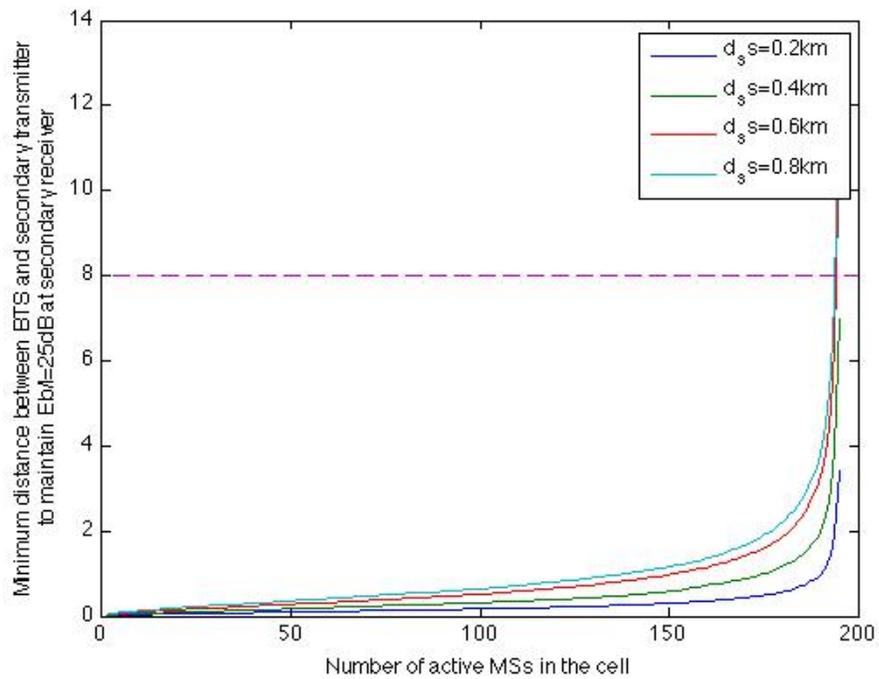


Figure 29. Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec}=20\text{dB}$$

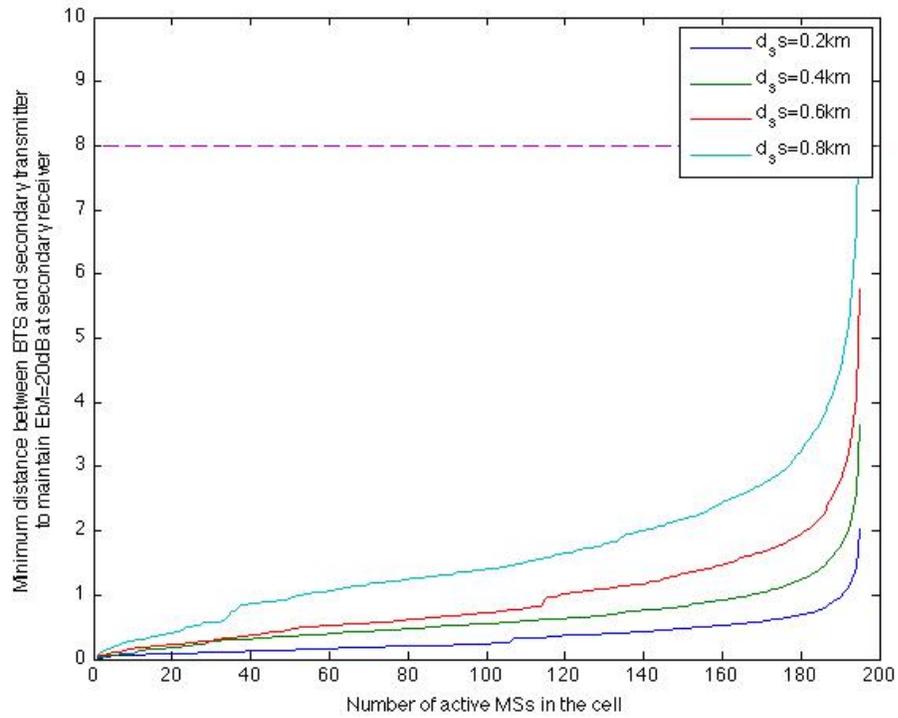


Figure 30. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

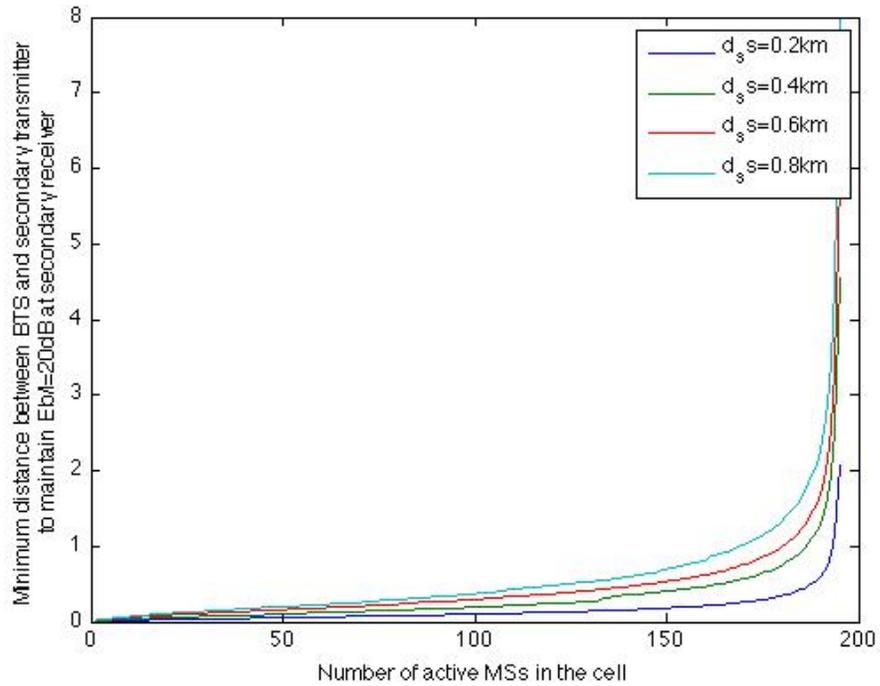


Figure 31. Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec} = 15 \text{ dB}$$

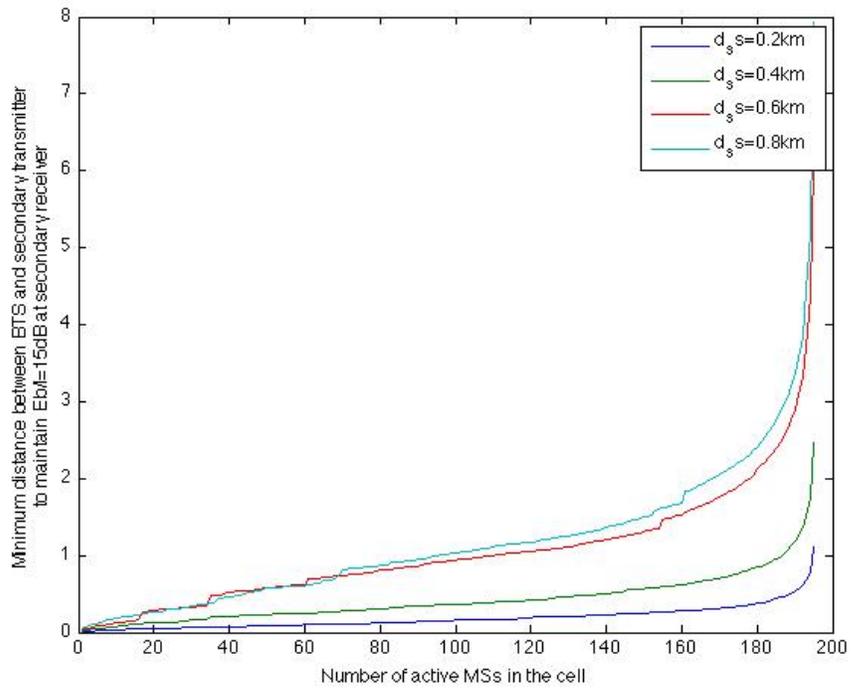


Figure 32. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

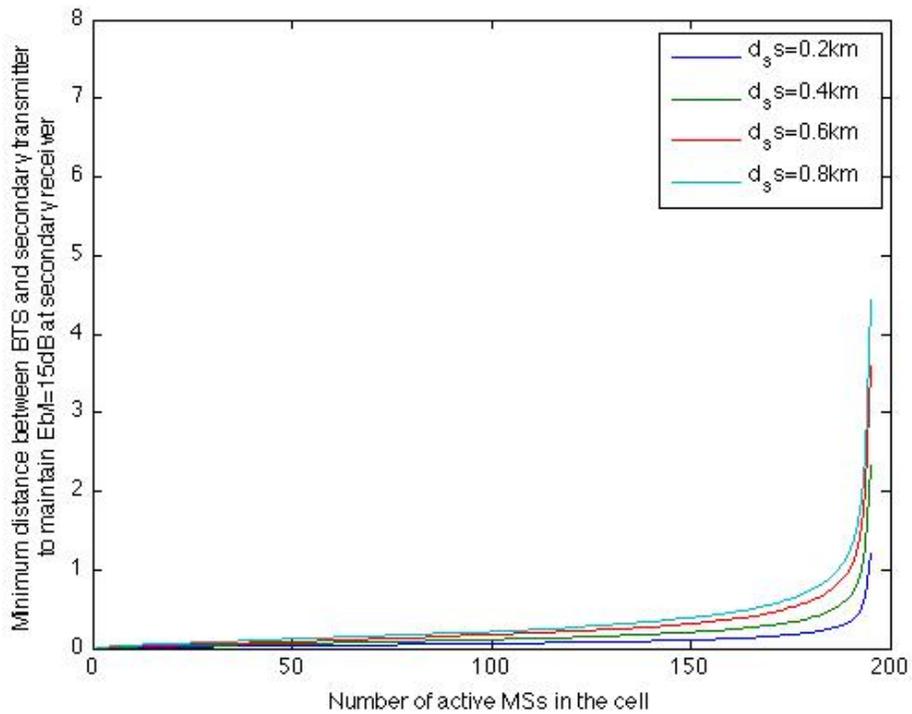


Figure 33. Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec} = 10\text{dB}$$

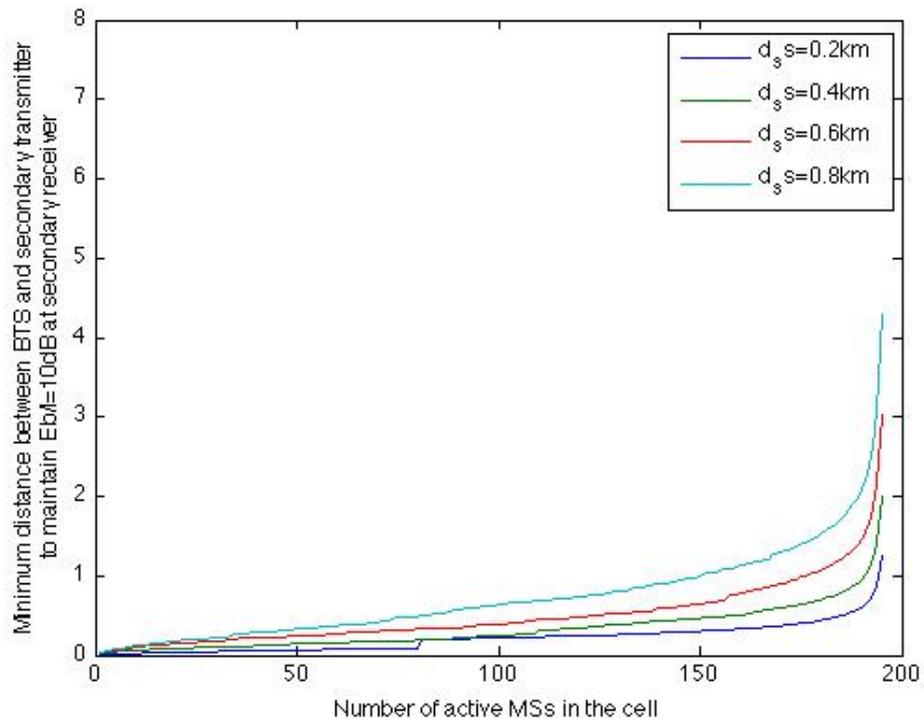


Figure 34. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

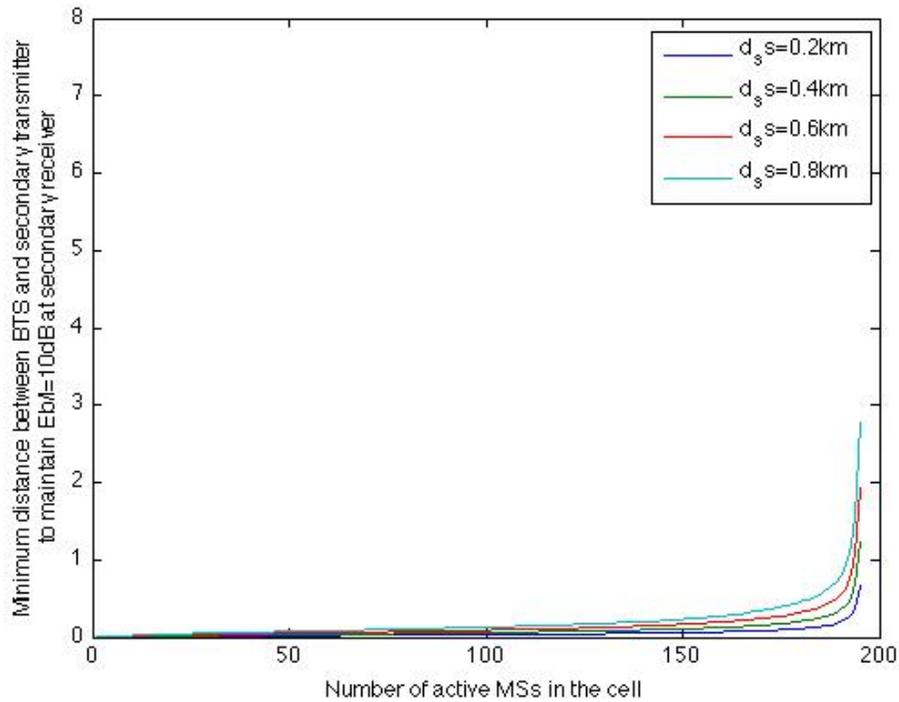
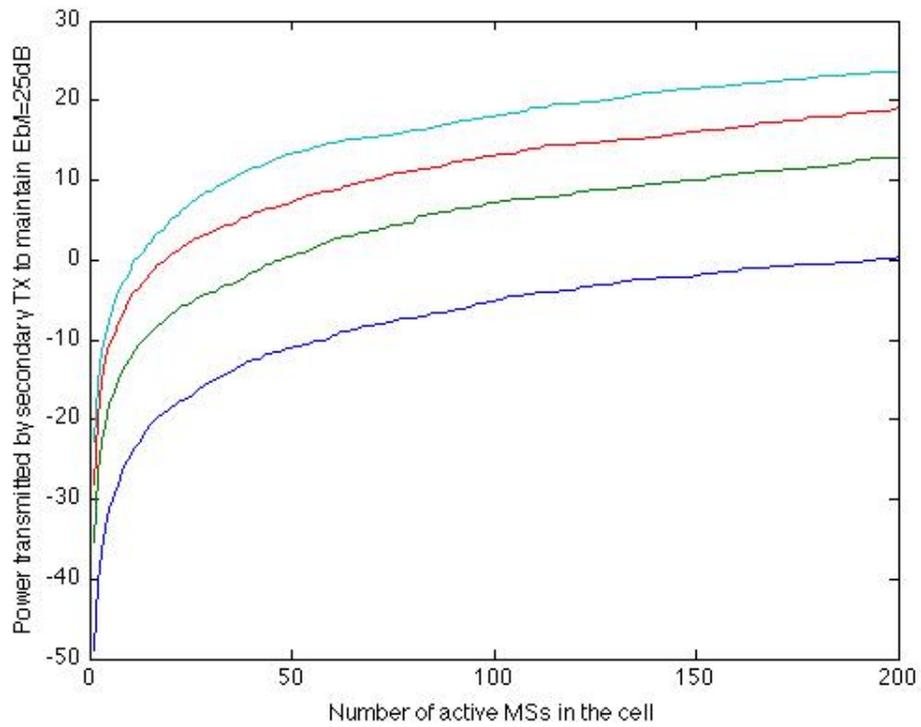


Figure 35. Minimum distance between BTS and secondary TX considering free space path loss model

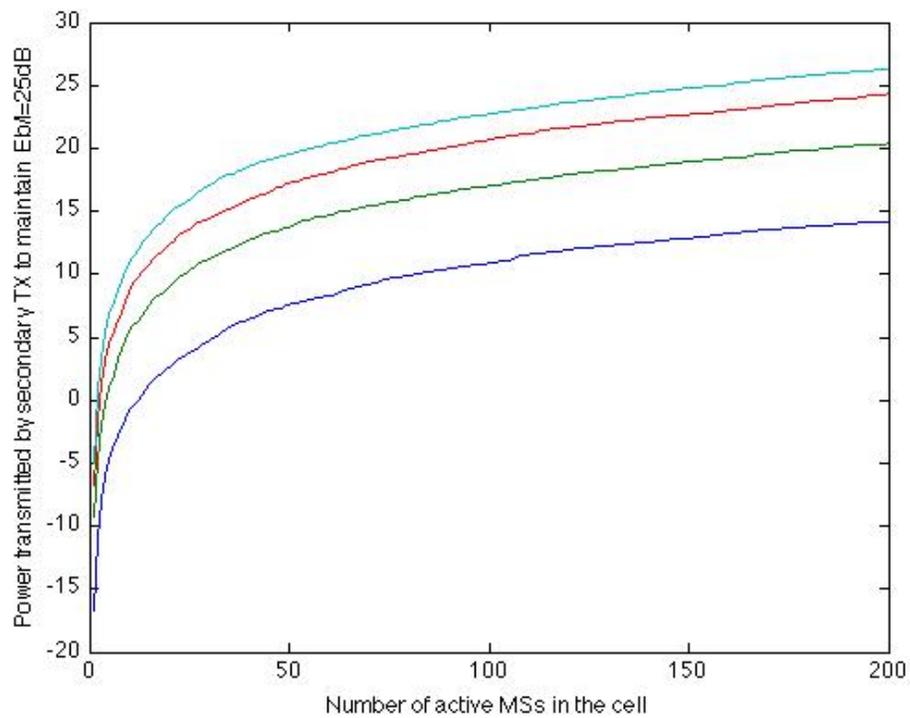
We can see from the above plots that when the number of active primary users (MSs in the figures) is not big, the distance between the secondary transmitter and BTS can be very small because there will not be big amount of interference coming from secondary transmissions to primary users. On the other hand it is clear that the higher the number of primary users  $-M$  is, the distance between the secondary TX and BTS has to be greater since the transmitting power of secondary TX needs to be increased to maintain the required quality level for the secondary receiver. It is clear from the plots that when the quality threshold at the secondary receiver is set lower, the minimum distance that needs to be kept between the secondary transmitter and BTS can also be smaller. Assuming the free space path-loss model, we see that the distance between the secondary transmitter and the BTS can be quite small even when there is a large number of active primary users. This is due to the fact that in free space conditions, due to the small power loss, even when the secondary is transmitting at higher power, the power received from primary MSs in BTS is high enough to ensure the required quality level.

7. In this case we found the same tradeoffs as in the 6-th one but we changed some parameters, such as:  $f_c=450$  MHz,  $h_m=2$ ,  $h_b=100$ ,  $h_{b\_sec}=10$ . See Figures 36 through 51.

$$E_b/I_{sec}=25\text{dB}$$

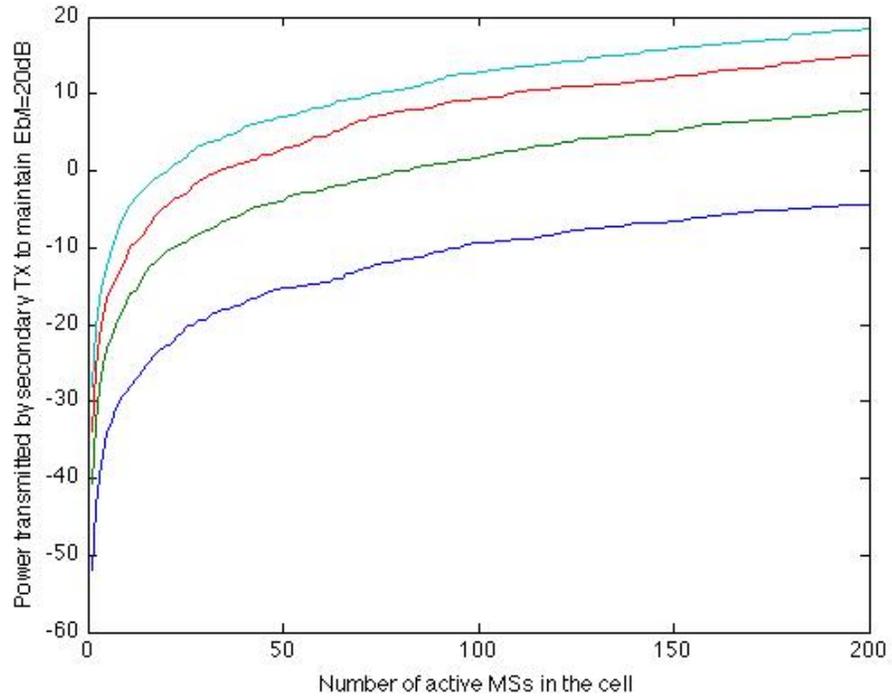


**Figure 36.** Power transmitted by secondary TX considering Okumura-Hata path-loss model

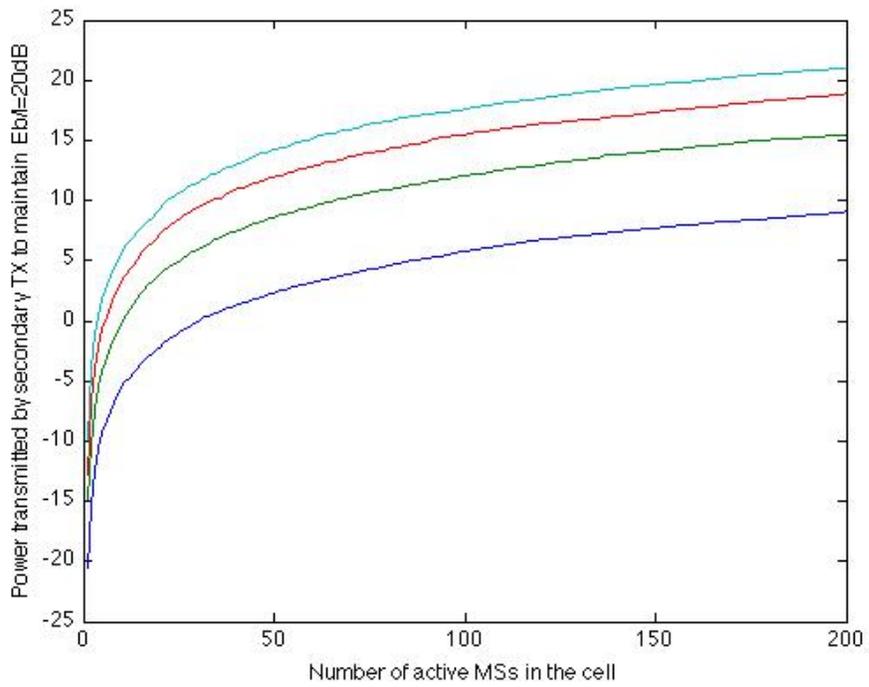


**Figure 37.** Power transmitted by secondary TX considering free space path-loss model

$$E_b/I_{sec} = 20 \text{ dB}$$

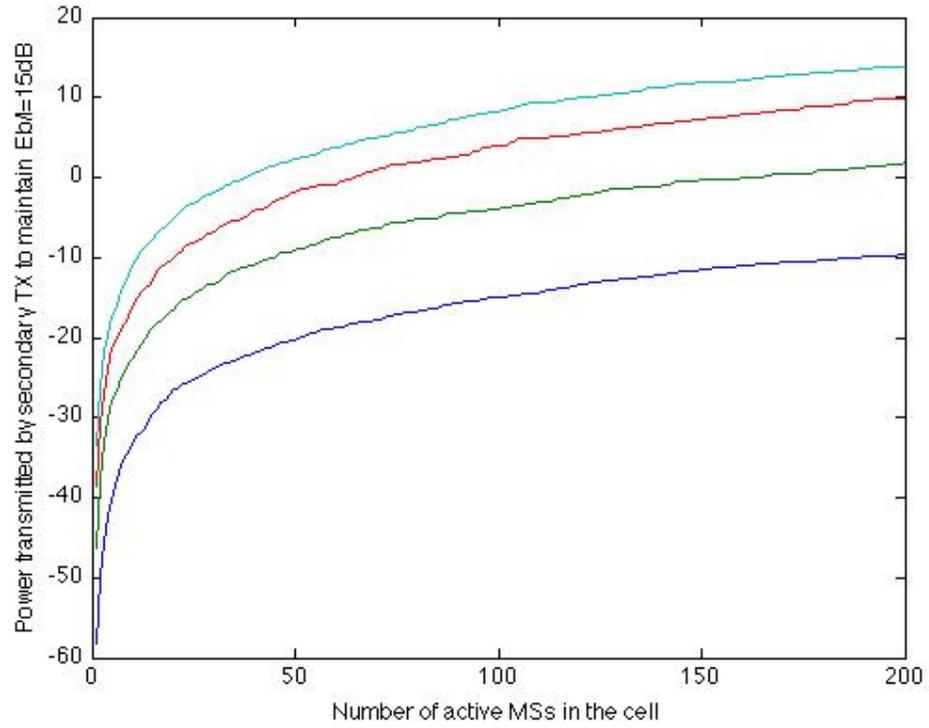


**Figure 38.** Power transmitted by secondary TX considering Okumura-Hata path-loss model

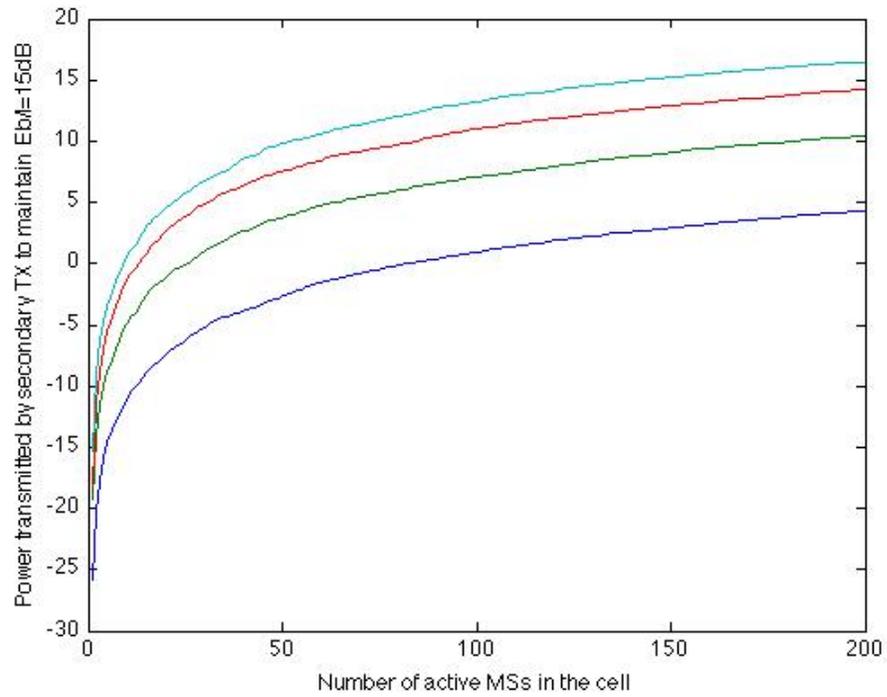


**Figure 39.** Power transmitted by secondary TX considering free space path-loss model

$$E_b/I_{sec} = 15 \text{ dB}$$

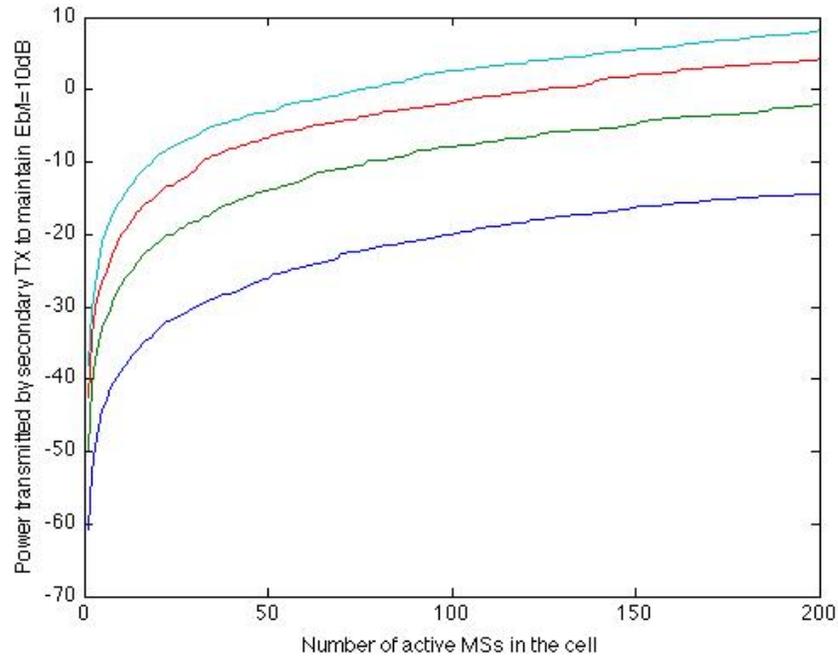


**Figure 40.** Power transmitted by secondary TX considering Okumura-Hata path-loss model

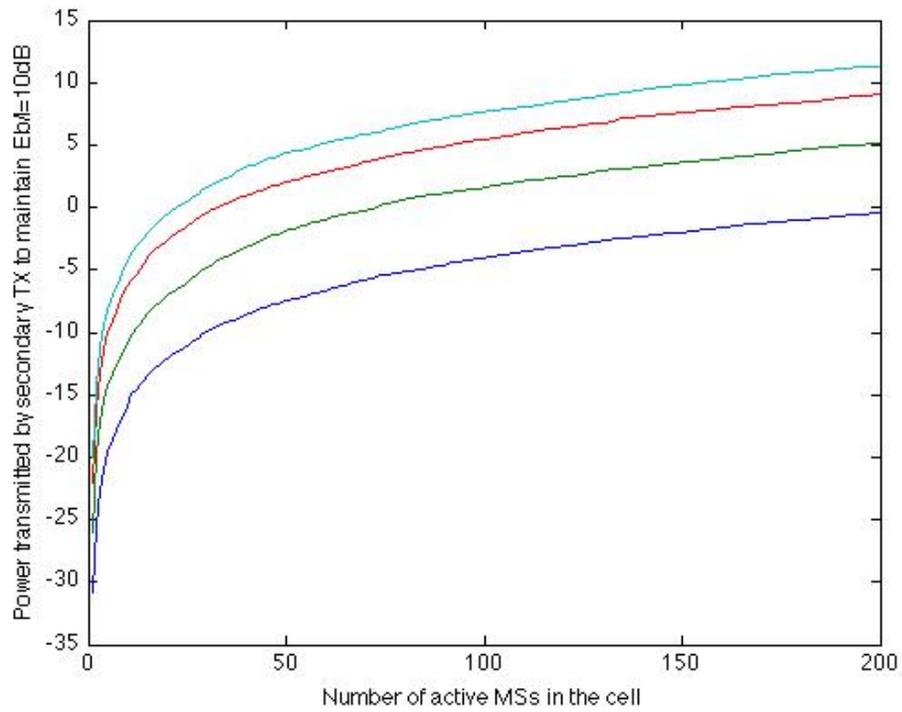


**Figure 41.** Power transmitted by secondary TX considering free space path-loss model

$$E_b/I_{sec} = 10 \text{ dB}$$



**Figure 42.** Power transmitted by secondary TX considering Okumura-Hata path-loss model



**Figure 43.** Power transmitted by secondary TX considering free space path-loss model

$$E_b/I_{sec} = 25\text{dB}$$

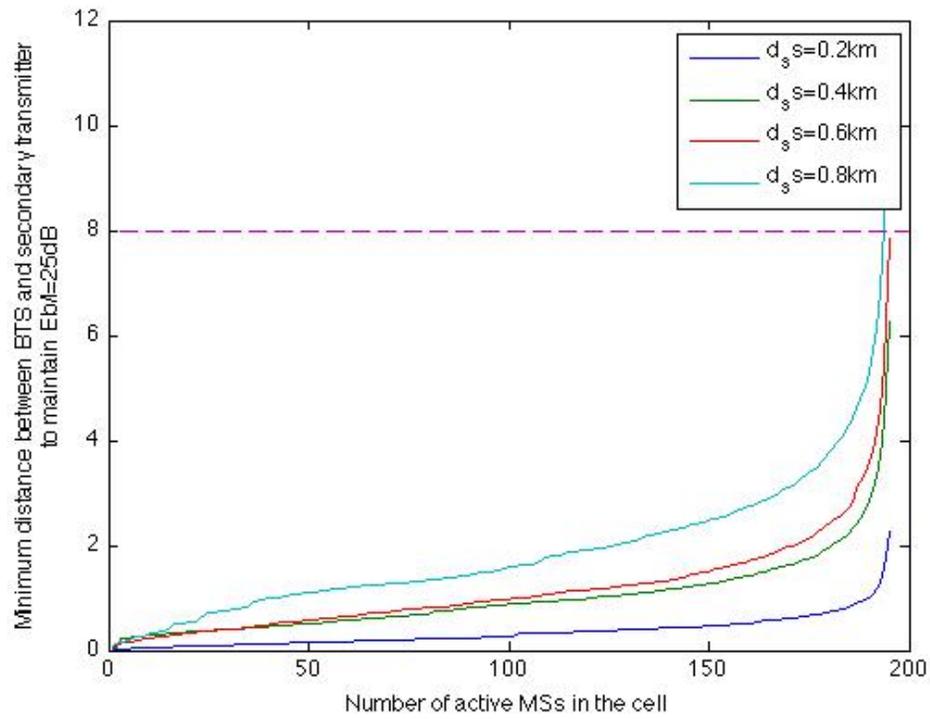


Figure 44. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

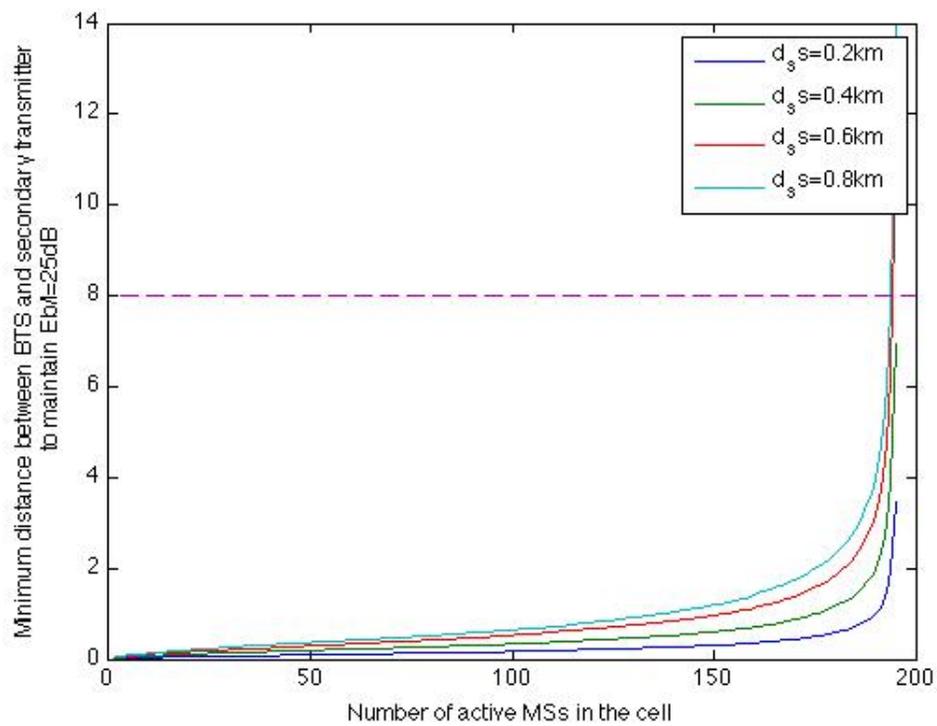
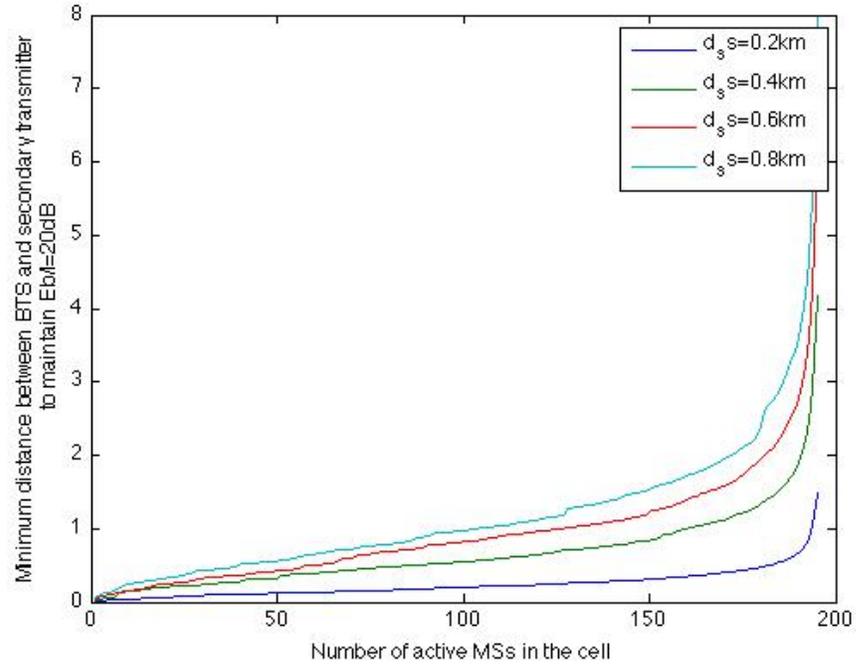
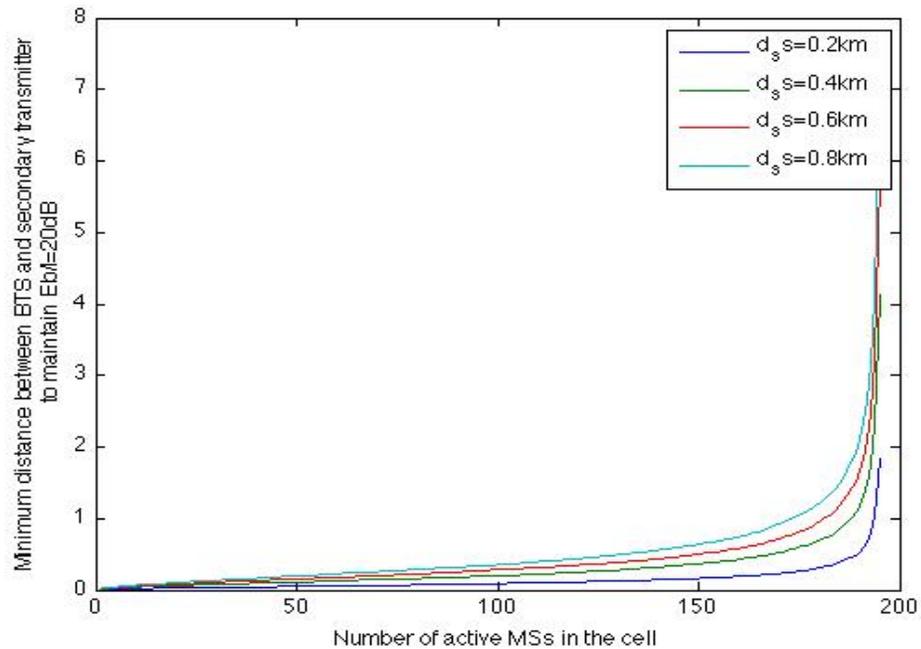


Figure 45. Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec} = 20 \text{ dB}$$



**Figure 46.** Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model



**Figure 47.** Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec} = 15 \text{ dB}$$

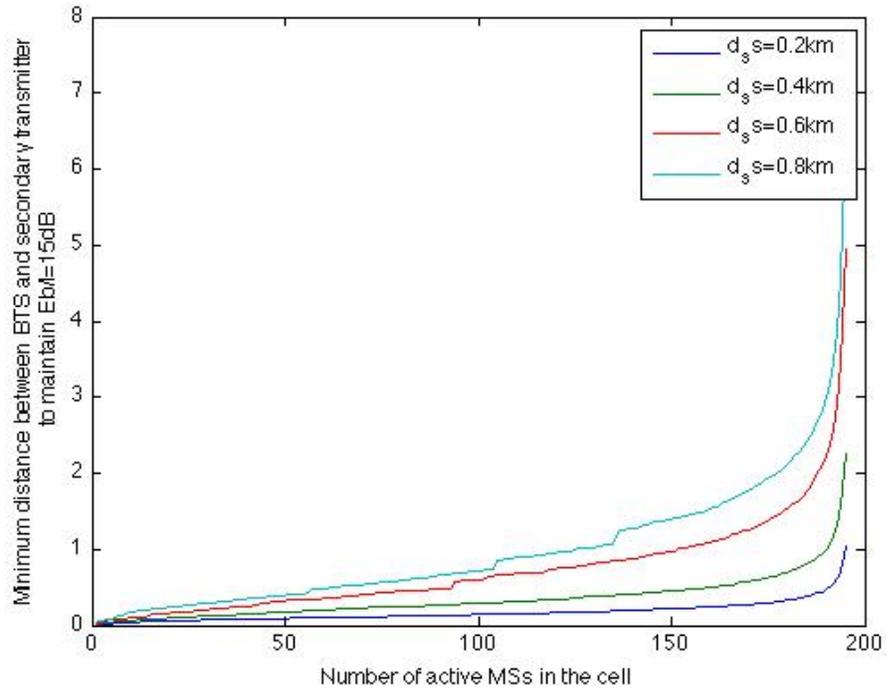


Figure 48. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

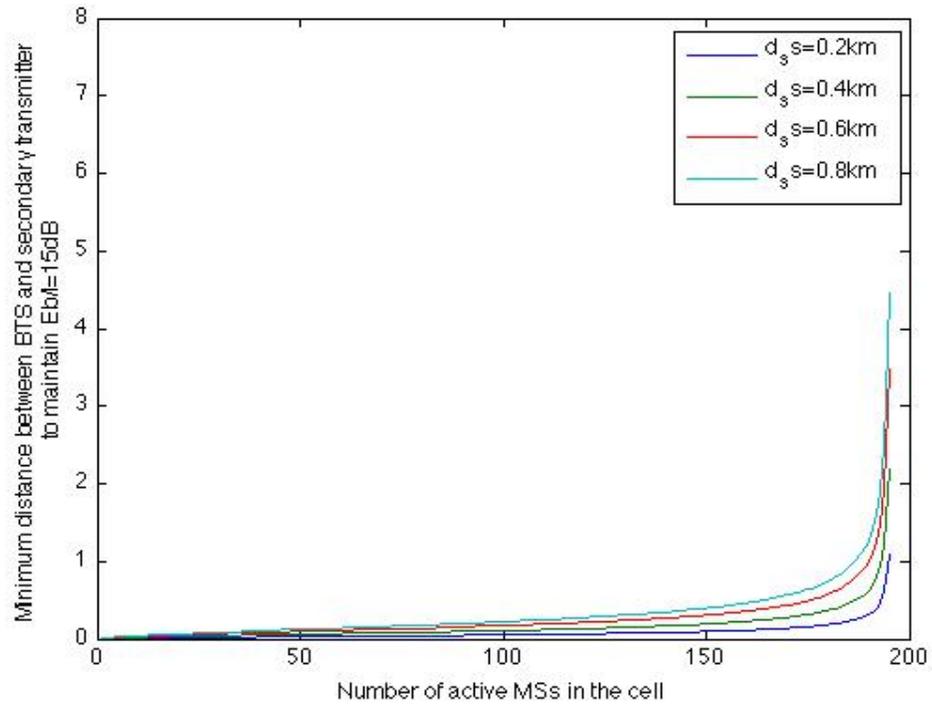


Figure 49. Minimum distance between BTS and secondary TX considering free space path loss model

$$E_b/I_{sec} = 10 \text{ dB}$$

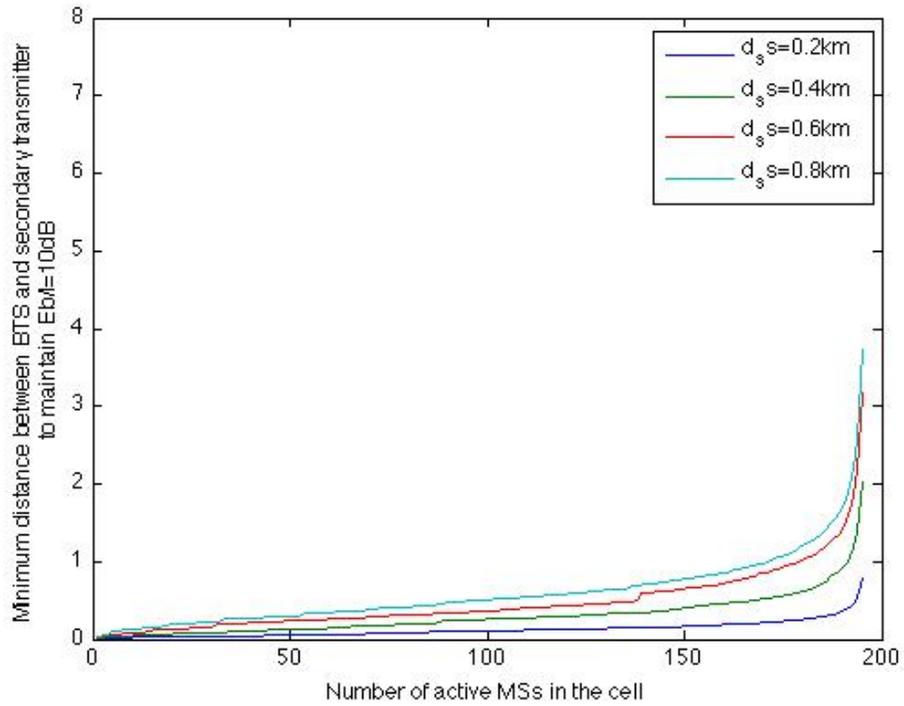


Figure 50. Minimum distance between BTS and secondary TX considering Okumura-Hata path loss model

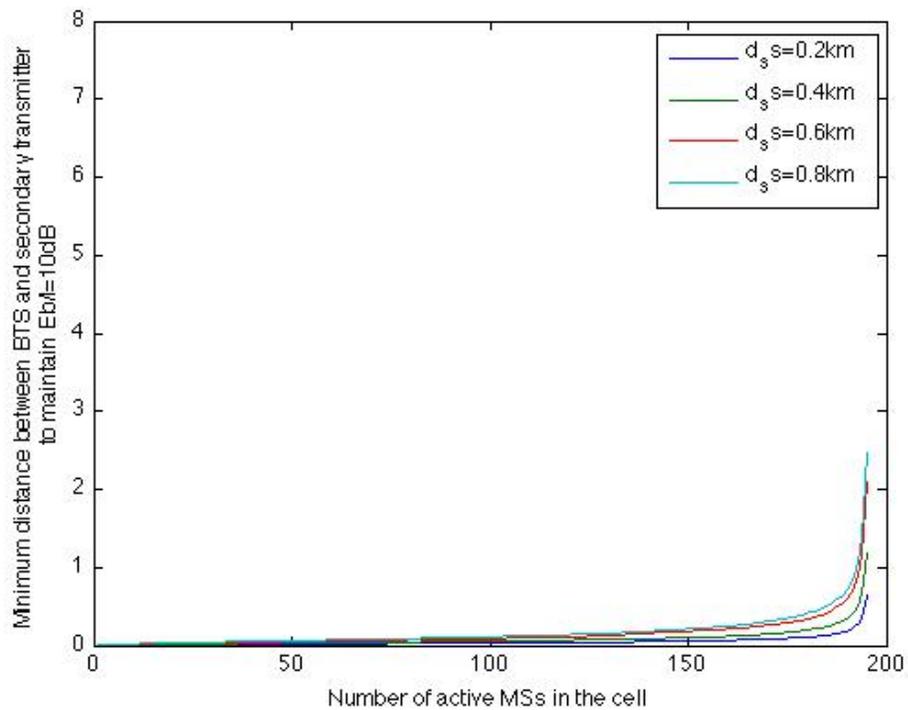
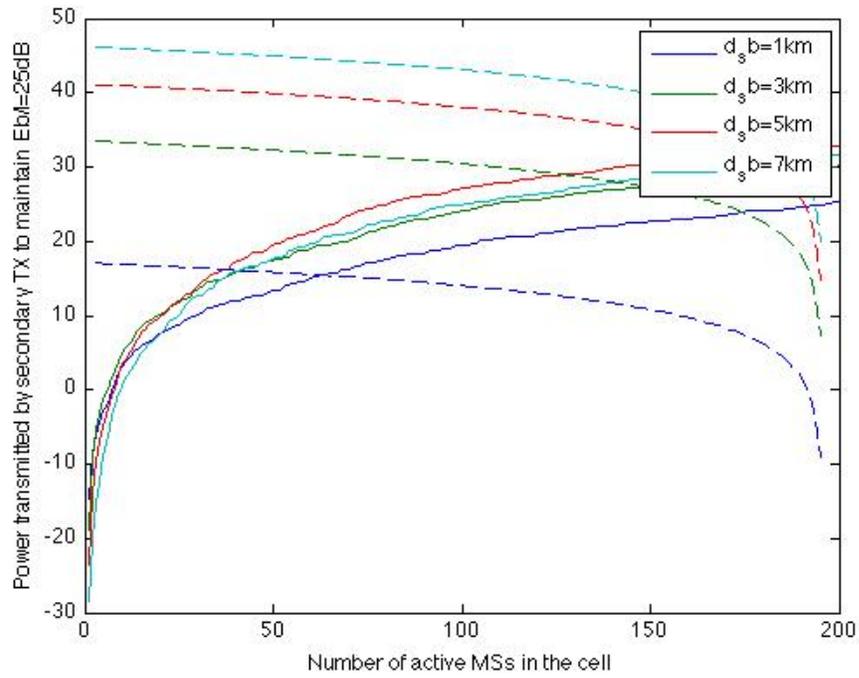


Figure 51. Minimum distance between BTS and secondary TX considering free space path loss model

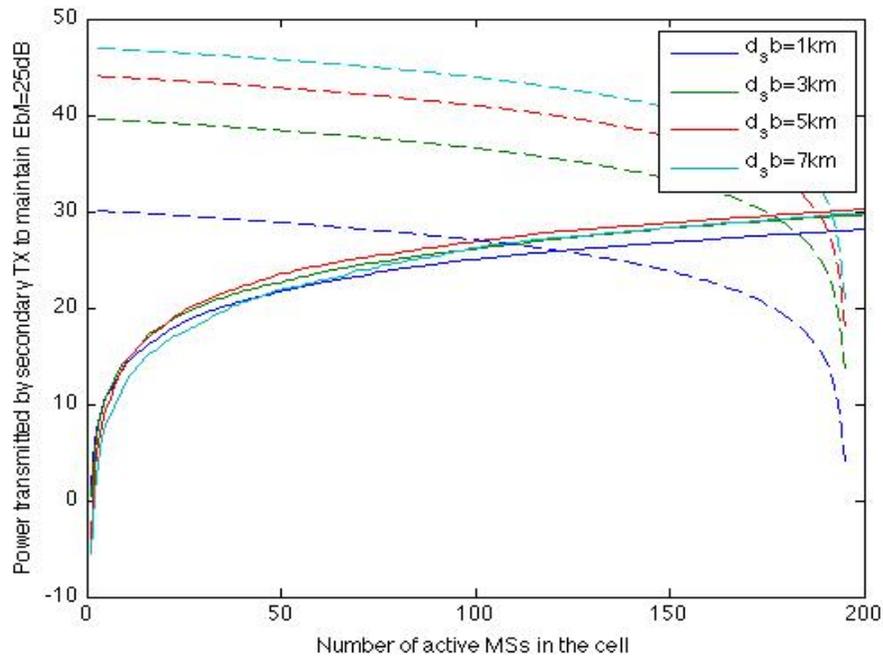
From the plots above we can see that there is not much of a difference in the maximum power transmitted from a secondary transmitter and the distance between secondary user and BTS if we change the carrier frequency and antenna heights of primary and secondary devices. Therefore the conclusions derived for the previous case are still valid.

**8a.** In the last case we derived the maximum allowed transmitted power for secondary transmitters from the equation for  $I_{sec}$  (see Equation 9). The distance between the secondary user and BTS changes 4 times: 1, 3, 5 and 7 km. We fixed the distance between the secondary TX and RX at different values. In this case  $d=1.2$  km and then we plotted together with power transmitted from secondary transmitter, taking into consideration only the  $E_b/I$  threshold in the secondary receiver which sets the minimum required transmit power. The dashed lines in the plots below represent the maximum allowed transmitting power calculated from the allowed interference. All these plots are as a function of the number of active primary users  $M$ . The intersection between the necessary transmit power and the maximum allowed power represents the maximum number of active MS users under which secondary network can still operate. See Figures 52 through 59.

$$E_b/I_{sec}=25 \text{ dB}$$

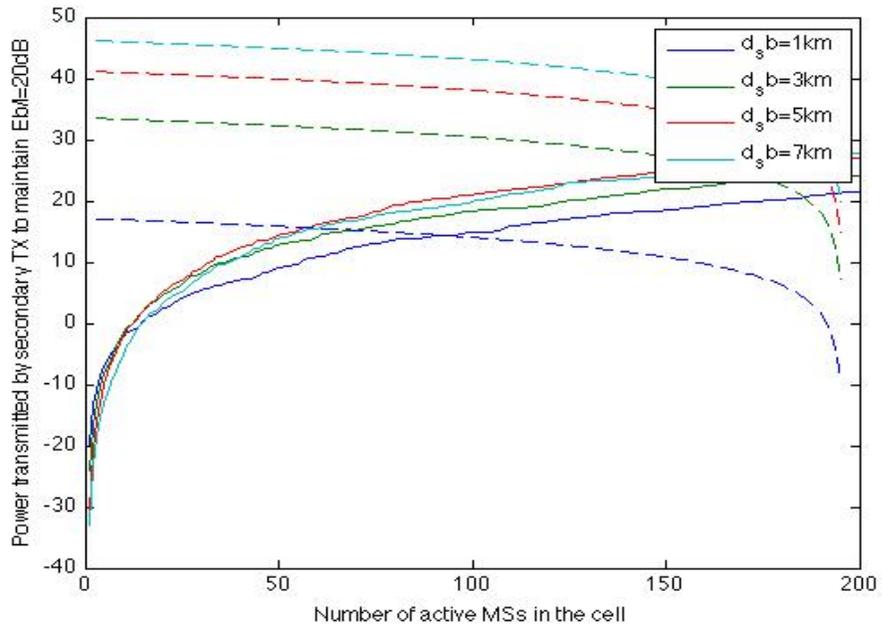


**Figure 52.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering Okumura-Hata path-loss model

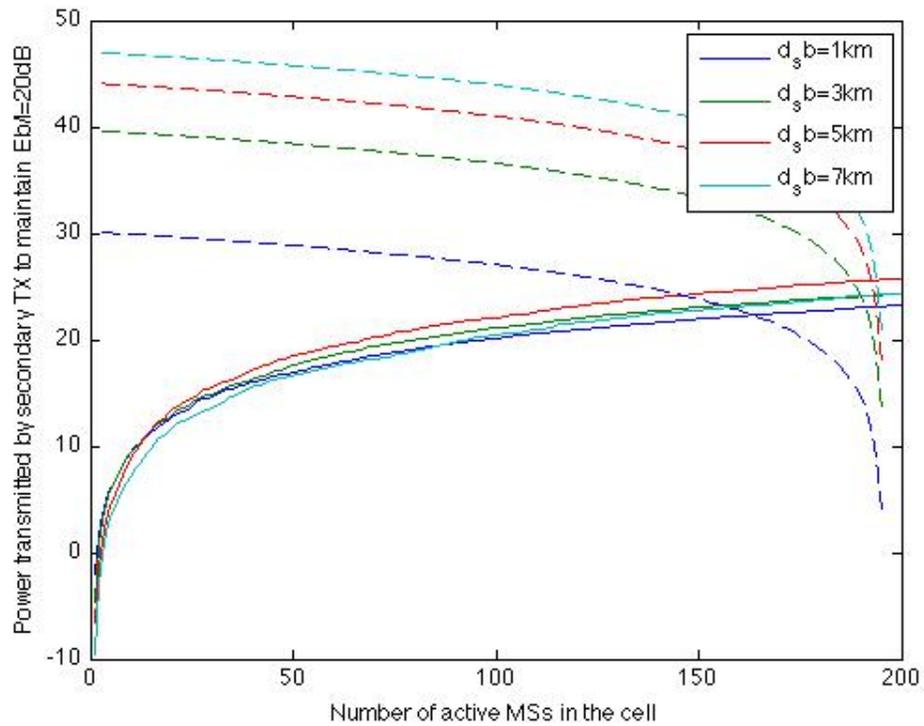


**Figure 53.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering free space path-loss model

$$E_b/I_{sec} = 20 \text{ dB}$$

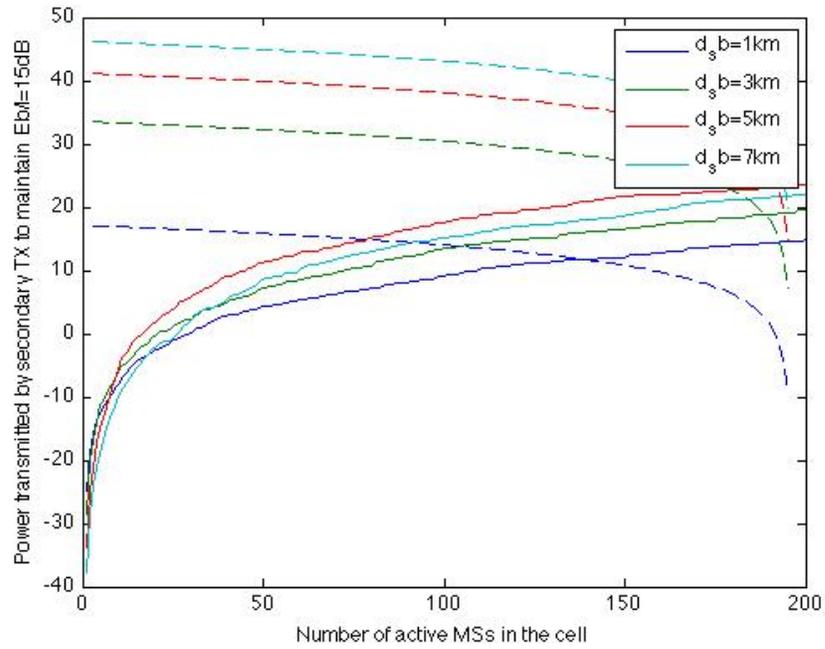


**Figure 54.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering Okumura-Hata path-loss model

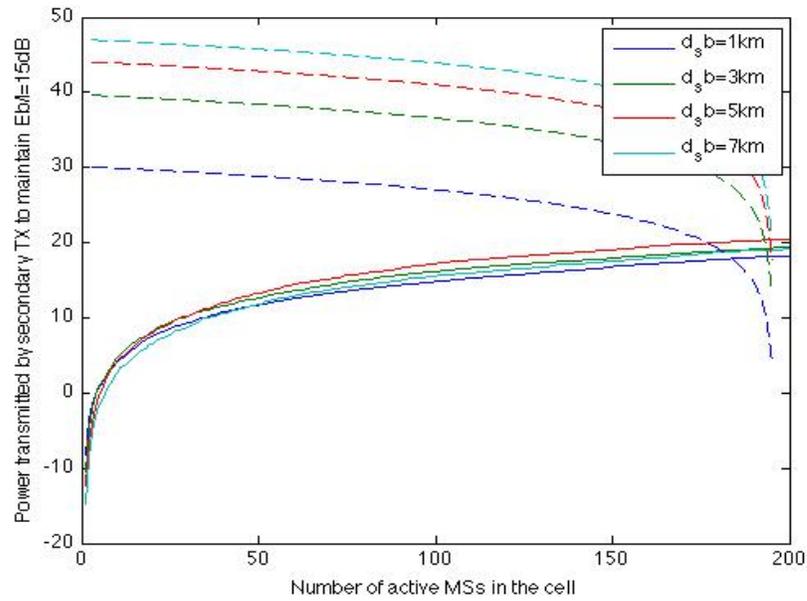


**Figure 55.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering free space path-loss model

$$E_b/I_{sec} = 15 \text{ dB}$$

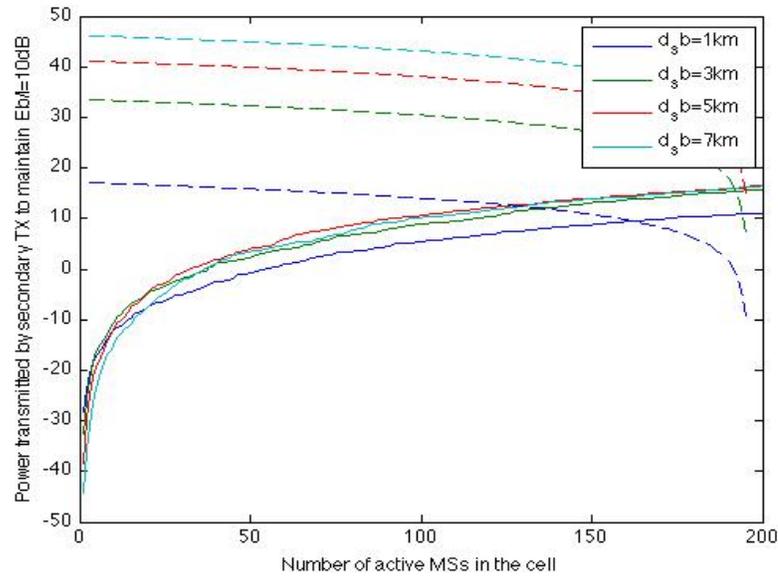


**Figure 56.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering Okumura-Hata path-loss model

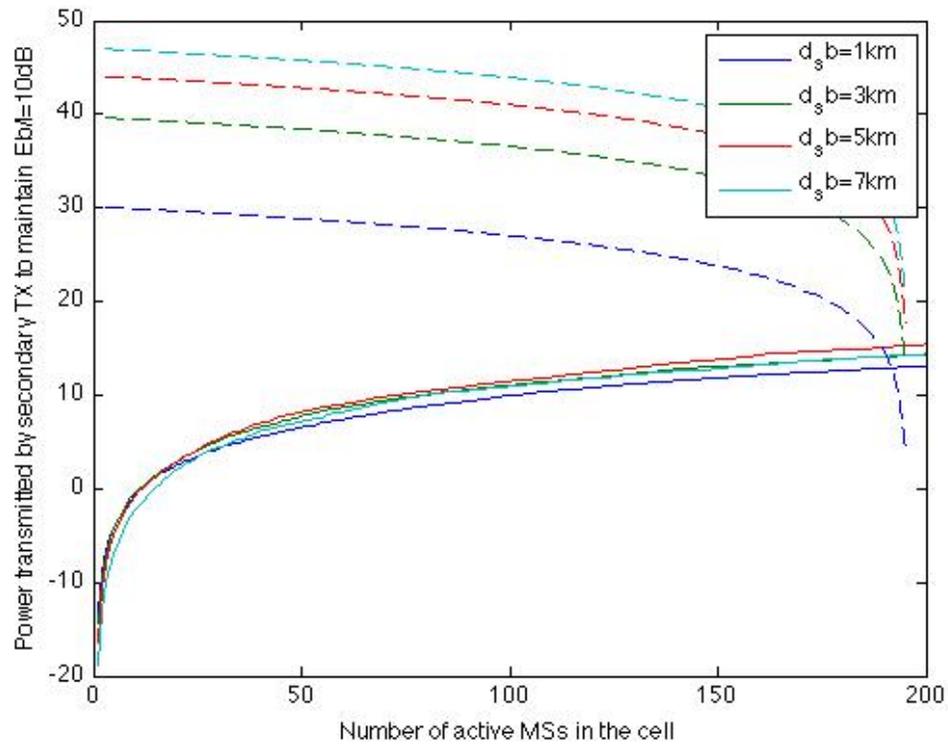


**Figure 57.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering free space path-loss model

$$E_b/I_{sec} = 10 \text{ dB}$$



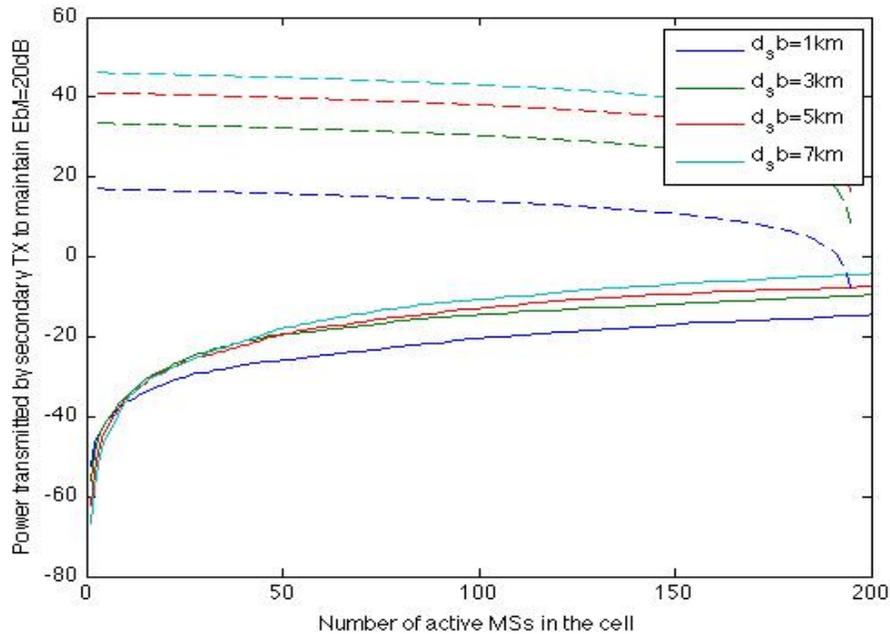
**Figure 58.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering Okumura-Hata path-loss model



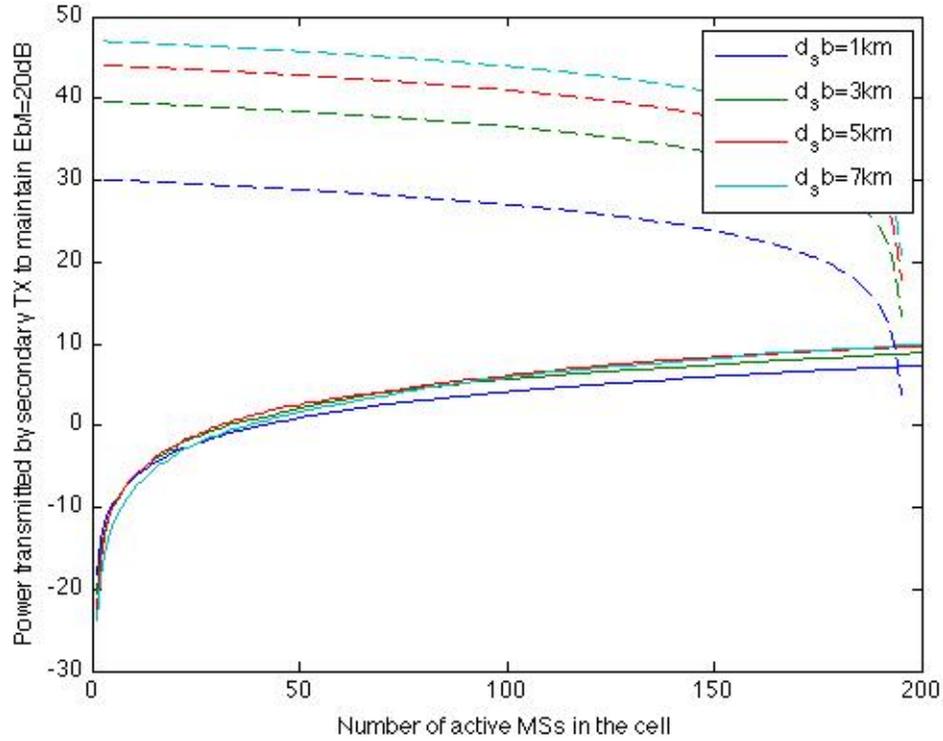
**Figure 59.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering free space path-loss model

From the plots above we can see that wherever the same colored lines intersect, that is basically the maximum allowed number of primary users  $M$  for this distance, for which secondary user can transmit meeting its own receiver's requirements. We can also notice that as the threshold at the secondary receiver is lowered, this intersection occurs further to the right, meaning that the maximum allowed number of primary users is increased for the same distance between secondary TX and BTS. From these plots, we can also observe more clearly that in free space path-loss conditions, for the same  $E_b/I$  threshold and distance between the secondary transmitter and the BTS, the intersection appears much more to the right, than in the Okumura-Hata path-loss conditions, and varies less with the distance between secondary and BTS. This leads to the intuitive conclusion, that in general, in free space conditions the opportunities for the secondary network to operate are much higher.

**8b.** Repeating this for the case when distance between secondary TX and RX  $d = 0.2$  km and considering only the case for  $E_b/I = 20$  dB, we get Figures 60 and 61



**Figure 60.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering Okumura-Hata path-loss model



**Figure 61.** Necessary transmitting power and maximum allowed transmitting power for secondary TX considering free space path-loss model

As was expected, Figures 60 and 60 show that the smaller the distance between the secondary TX and RX is, the larger is the number of primary users  $M$  that can be active in the system and still a secondary user will be able to transmit meeting its requirements.

## **5.0 CONCLUSIONS**

We can say that based on simulations, a secondary user has a good chance of operating in vacant bands of primary users as long as it operates under certain restrictions:

- Secondary transmission can occur in a cell when the utilization of the cell is not high
- Secondary user can achieve the power transmitted necessary to fulfill secondary receiver requirements over short distances between secondary TX and secondary RX
- Having a threshold in a secondary RX is a better approach because it shows the real maximum transmitted power
- Depending on the threshold that is set at a secondary RX and the environment (path-loss model) the restriction under which the secondary user can operate can be tightened or loosened.

### **5.1 FUTURE WORK:**

All of this work has been done by taking into consideration one secondary user transmitting in the cell. After we calculate the amount of interference caused in a secondary receiver from the active primary users in the cell, we can find the number of secondary users supported in the cell.

In this work, we also ignored the interference that comes in receivers from adjacent cells. Taking that into consideration implies that the interference level will increase which means that the number of users (primary first and then also secondary ones) will decrease.

Knowing the allowed power transmitted from a secondary device, we can also know what type of applications the secondary users can employ and what type of data rates they will be able to support.

## APPENDIX A

### [MATLAB CODE]

#### Code used to generate Figures 6 and 7

```
close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;

R=8;%km
for M=1:1:190
landa = 3*10^8/(fc*10^6);
Lp_ms_bts=21.98-20*log10(landa)+20*log10(R*10^3);

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;`
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
```

```

%
Isec(M)=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;

end

plot(1:M,Isec);
xlabel('Number of active MSs');
ylabel('Maximum interference from secondary in W');

```

### Code used to generate Figures 8 and 9

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;

R=8;%km
for M=1:1:190
landa = 3*10^8/(fc*10^6);
Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;`
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;

%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm(M) = 10*log10(Pr_bts_sec/10^-3);

end

```

```

plot(1:M,Pr_bts_sec_dbm);
xlabel('Number of active MSs');
ylabel('Maximum power received from secondary in dBm');

```

## Code used to generate figures 10 and 11

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;

R=8;%km
for M=1:1:190
landa = 3*10^8/(fc*10^6);
Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;`
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;

%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm(M) = 10*log10(Pr_bts_sec/10^-3);

end
d_sec= 0.1:0.1:8;

% Calculatin path loss between secondary and bts for different values of
% distance

```

```

Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec)-
13.82*log10(hb)-ahm;

%Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
figure(1)
plot(1:M,Pr_bts_sec_dbm);
xlabel('Number of active MSs');
ylabel('Maximum power received from secondary in dBm')

%Plotting the transmitting power of the secondary versus the distance from
%bts with fixed number of M

%for M=10
Pt_sec(1,:)=Pr_bts_sec_dbm(10)*ones(1,80)+Lp_bts_sec;

%for M=30
Pt_sec(2,:)=Pr_bts_sec_dbm(30)*ones(1,80)+Lp_bts_sec;

%for M=60
Pt_sec(3,:)=Pr_bts_sec_dbm(60)*ones(1,80)+Lp_bts_sec;

%for M=80
Pt_sec(4,:)=Pr_bts_sec_dbm(80)*ones(1,80)+Lp_bts_sec;

%for M=110
Pt_sec(5,:)=Pr_bts_sec_dbm(110)*ones(1,80)+Lp_bts_sec;

%for M=140
Pt_sec(6,:)=Pr_bts_sec_dbm(140)*ones(1,80)+Lp_bts_sec;

%for M=180
Pt_sec(7,:)=Pr_bts_sec_dbm(180)*ones(1,80)+Lp_bts_sec;
figure(3)
plot(d_sec,Pt_sec(1,:),d_sec,Pt_sec(2,:),d_sec,Pt_sec(3,:),d_sec,Pt_sec(4,:),
d_sec,Pt_sec(5,:),d_sec,Pt_sec(6,:),d_sec,Pt_sec(7,:))
legend('M=10','M=30','M=60','M=80','M=110','M=140','M=180');
xlabel('Distance between secondary and BTS (km)');
ylabel('Maximum power transmitted by the secondary (dBm)');

```

### Code used to generate Figures 12 and 13

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;

R=8;%km

```

```

for M=1:1:190
landa = 3*10^8/(fc*10^6);
Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;`
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;

%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm(M) = 10*log10(Pr_bts_sec/10^-3);

end
d_sec= 0.1:0.1:8;

% Calculatin path loss between secondary and bts for different values of
% distance
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec)-
13.82*log10(hb)-ahm;

%Lp_bts_sec=21.98-20*log10(landa)+20*log10(d_sec*10^3);

%Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
figure(1)
plot(1:M,Pr_bts_sec_dbm);
xlabel('Number of active MSs');
ylabel('Maximum power received from secondary in dBm')

Pr_sec_sec_dbm=-90;% power received threshold at secondary receiver from
secondary transmitter

%% Finding the minimum distance between secondary transmitter and bts when
%% fixing the distance between secondary transmitter and receiver
d_ss=0.1;%km
hbsec =2;%m

```

```

Lp_sec_sec(1,:)=69.55+26.16*log10(fc)+(44.9-6.55*log10(hbsec))*log10(d_ss)-
13.82*log10(hbsec)-ahm; %path loss between secondary tx and rx
Pt_sec3(1,:)=Pr_sec_sec_dbm+Lp_sec_sec(1,:); % power transmitted at secondary
transmitter

Lp_sec_bts_allowed(1,:)= Pt_sec3(1,:)*ones(1,190)-Pr_bts_sec_dbm; % path loss
allowed between secondary transmitter and bts considet powet transmitted and
power received at bts (ISsec)

d_sec_allowed(1,:)= 10.^((Lp_sec_bts_allowed(1,:)-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb))); %minimum
distance allowed between secondary tx and bts

%%%
d_ss=0.2;%km
hbsec =2;%m
Lp_sec_sec(2,:)=69.55+26.16*log10(fc)+(44.9-6.55*log10(hbsec))*log10(d_ss)-
13.82*log10(hbsec)-ahm;
Pt_sec3(2,:)=Pr_sec_sec_dbm+Lp_sec_sec(2,:);

Lp_sec_bts_allowed(2,:)= Pt_sec3(2,:)*ones(1,190)-Pr_bts_sec_dbm;

d_sec_allowed(2,:)= 10.^((Lp_sec_bts_allowed(2,:)-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));

%%%
d_ss=0.3;%km
hbsec =2;%m
Lp_sec_sec(3,:)=69.55+26.16*log10(fc)+(44.9-6.55*log10(hbsec))*log10(d_ss)-
13.82*log10(hbsec)-ahm;
Pt_sec3(3,:)=Pr_sec_sec_dbm+Lp_sec_sec(3,:);

Lp_sec_bts_allowed(3,:)= Pt_sec3(3,:)*ones(1,190)-Pr_bts_sec_dbm;

d_sec_allowed(3,:)= 10.^((Lp_sec_bts_allowed(3,:)-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));

%%%
d_ss=0.4;%km
hbsec =2;%m
Lp_sec_sec(4,:)=69.55+26.16*log10(fc)+(44.9-6.55*log10(hbsec))*log10(d_ss)-
13.82*log10(hbsec)-ahm;
Pt_sec3(4,:)=Pr_sec_sec_dbm+Lp_sec_sec(4,:);

Lp_sec_bts_allowed(4,:)= Pt_sec3(4,:)*ones(1,190)-Pr_bts_sec_dbm;

d_sec_allowed(4,:)= 10.^((Lp_sec_bts_allowed(4,:)-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
%%%
d_ss=0.5;%km
hbsec =2;%m

```

```

Lp_sec_sec(5,:) = 69.55 + 26.16 * log10(fc) + (44.9 - 6.55 * log10(hbsec)) * log10(d_ss) -
13.82 * log10(hbsec) - ahm;
Pt_sec3(5,:) = Pr_sec_sec_dbm + Lp_sec_sec(5,:);

Lp_sec_bts_allowed(5,:) = Pt_sec3(5,:) * ones(1,190) - Pr_bts_sec_dbm;

d_sec_allowed(5,:) = 10.^((Lp_sec_bts_allowed(5,:) - 69.55 -
26.16 * log10(fc) + 13.82 * log10(hb) + ahm) / (44.9 - 6.55 * log10(hb)));

%%%

d_ss = 0.8; %km
hbsec = 2; %m
Lp_sec_sec(6,:) = 69.55 + 26.16 * log10(fc) + (44.9 - 6.55 * log10(hb)) * log10(d_ss) -
13.82 * log10(hbsec) - ahm;
Pt_sec3(6,:) = Pr_sec_sec_dbm + Lp_sec_sec(6,:);

Lp_sec_bts_allowed(6,:) = Pt_sec3(6,:) * ones(1,190) - Pr_bts_sec_dbm;

d_sec_allowed(6,:) = 10.^((Lp_sec_bts_allowed(6,:) - 69.55 -
26.16 * log10(fc) + 13.82 * log10(hb) + ahm) / (44.9 - 6.55 * log10(hb)));

figure(4)
plot(1:M, d_sec_allowed);

legend('d_ss=0.1km', 'd_ss=0.2km', 'd_ss=0.3km', 'd_ss=0.4km', 'd_ss=0.5km', 'd_ss=
=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Minimum distance allowed between secondary TX and BTS');

```

## Code used to generate Figures 14 and 15

```

close all;
clear all;
Pt_ms = 316 * 10^-3; %Watt
%Path loss model : Ohumura-Hata
fc = 880; %Mhz
hm = 2; %m
hb = 40; %m
hbsec = 2; %m
ahm = 3.2 * (log10(11.75 * hm))^2 - 4.97;

R = 8; %km
for M = 1:1:190
landa = 3 * 10^8 / (fc * 10^6);
Lp_ms_bts = 69.55 + 26.16 * log10(fc) + (44.9 - 6.55 * log10(hb)) * log10(R) -
13.82 * log10(hb) - ahm;
%Lp_ms_bts = 21.98 - 20 * log10(landa) + 20 * log10(R * 10^3);

Pr_bts_ms = Pt_ms / 10^(Lp_ms_bts / 10);
Pr_bts_ms_dbm = 10 * log10(Pr_bts_ms / 10^-3);

```

```

Bw=5000; %khz;`
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;

%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm(M) = 10*log10(Pr_bts_sec/10^-3);

end

Pr_sec_sec_dbm=-90;% power received threshold at secondary receiver from
secondary transmitter
%%Finding the maximum distance between secondary transmitter and receiver
%%when fixing the distance between secondary transmitter and bts
d_sec= 0.1:0.1:8;

% Calculatin path loss between secondary and bts for different values of
% distance
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec)-
13.82*log10(hb)-ahm;

d_sb=1;%km
Pt_sec4(1,:)=Lp_bts_sec(10)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(1,:)=Pt_sec4(1,:)-Pr_sec_sec_dbm;
d_ss_allowed(1,:)= 10.^((Lp_sec_sec_allowed(1,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=2;%km
Pt_sec4(2,:)=Lp_bts_sec(20)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(2,:)=Pt_sec4(2,:)-Pr_sec_sec_dbm;
d_ss_allowed(2,:)= 10.^((Lp_sec_sec_allowed(2,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=3;%km
Pt_sec4(3,:)=Lp_bts_sec(30)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(3,:)=Pt_sec4(3,:)-Pr_sec_sec_dbm;
d_ss_allowed(3,:)= 10.^((Lp_sec_sec_allowed(3,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

```

```

d_sb=4;%km
Pt_sec4(4,:)=Lp_bts_sec(40)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(4,:)=Pt_sec4(4,:)-Pr_sec_sec_dbm;
d_ss_allowed(4,:)= 10.^((Lp_sec_sec_allowed(4,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=5;%km
Pt_sec4(5,:)=Lp_bts_sec(50)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(5,:)=Pt_sec4(5,:)-Pr_sec_sec_dbm;
d_ss_allowed(5,:)= 10.^((Lp_sec_sec_allowed(5,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=6;%km
Pt_sec4(6,:)=Lp_bts_sec(60)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(6,:)=Pt_sec4(6,:)-Pr_sec_sec_dbm;
d_ss_allowed(6,:)= 10.^((Lp_sec_sec_allowed(6,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=7;%km
Pt_sec4(7,:)=Lp_bts_sec(70)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(7,:)=Pt_sec4(7,:)-Pr_sec_sec_dbm;
d_ss_allowed(7,:)= 10.^((Lp_sec_sec_allowed(7,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

d_sb=8;%km
Pt_sec4(8,:)=Lp_bts_sec(80)+Pr_bts_sec_dbm;
Lp_sec_sec_allowed(8,:)=Pt_sec4(8,:)-Pr_sec_sec_dbm;
d_ss_allowed(8,:)= 10.^((Lp_sec_sec_allowed(8,:)-69.55-
26.16*log10(fc)+13.82*log10(hbsec)+ahm)/(44.9-6.55*log10(hbsec)));

figure(5)
plot(1:M,d_ss_allowed);
legend('d_sb=1km','d_sb=2km','d_sb=3km','d_sb=4km','d_sb=5km','d_sb=6km','d_s
b=7km','d_sb=8km');
xlabel('Number of active MSs in the cell');
ylabel('Maximum distance allowed between secondary TX and secondary RX');

```

## Code used to generate Figures 16 and 17

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
for d_sec_bts = 1:2:8; %km
%for d_sec_sec =0.2:0.2:0.8

```

```

%d_sec_bts =4;%km
d_sec_sec = 0.8;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);
for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec_th_db=25;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;

```

```

Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

Pt_sec_sec_temp_dbm=zeros(1,N);
d_sec_allowed_temp=zeros(1,N);

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

%
% scatter([sec_tx_x,0],[sec_tx_y,0],'red');
% scatter(sec_rx_x,sec_rx_y, 'green');
%
% plot(R*cos([0:0.1:2*pi]),R*sin([0:0.1:2*pi]));

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_th= 10^(Eb_I_sec_th_db/10);
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;
Pr_sec_sec_dbm = Pt_sec_dbm_max(Mloop,dloop)-Lp_sec_sec;
Pr_sec_sec=10^(-3)*10.^(Pr_sec_sec_dbm/10);
Eb_I_sec_temp(Mloop,i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_th*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
Mloop=Mloop+1;
%d_sec_allowed_temp(i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
end

%d_sec_allowed(Mloop,dloop)=sum(d_sec_allowed_temp)/length(d_sec_allowed_temp
);

```

```

end
%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
    Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
    Eb_I_sec_temp_sum=sum(Eb_I_sec_temp');
    Eb_I_sec(:,dloop)=Eb_I_sec_temp_sum/N;

else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
    Eb_I_sec(:,dloop)=Eb_I_sec_temp;
end
dloop=dloop+1;
end
figure(1)
plot(1:1:M,Eb_I_sec);
legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
% hold
% plot(1:1:M,Pt_sec_dbm_max,'--');

%legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Eb/I at the secondary receiver');
%Pt_sec_max

```

### Code used to generate Figures 18 and 19

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
%for d_sec_bts = 1:2:8; %km
for d_sec_sec =0.2:0.2:0.8
d_sec_bts =4;%km
%d_sec_sec = 0.8;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

```

```

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);
for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec_th_db=25;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;
Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

Pt_sec_sec_temp_dbm=zeros(1,N);
d_sec_allowed_temp=zeros(1,N);

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

```

```

%
% scatter([sec_tx_x,0],[sec_tx_y,0],'red');
% scatter(sec_rx_x,sec_rx_y, 'green');
%
% plot(R*cos([0:0.1:2*pi]),R*sin([0:0.1:2*pi]));

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_th= 10^(Eb_I_sec_th_db/10);
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;
Pr_sec_sec_dbm = Pt_sec_dbm_max(Mloop,dloop)-Lp_sec_sec;
Pr_sec_sec=10^(-3)*10.^(Pr_sec_sec_dbm/10);
Eb_I_sec_temp(Mloop,i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_th*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
Mloop=Mloop+1;
%d_sec_allowed_temp(i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
end

%d_sec_allowed(Mloop,dloop)=sum(d_sec_allowed_temp)/length(d_sec_allowed_temp
);

end
%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
    Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
    Eb_I_sec_temp_sum=sum(Eb_I_sec_temp');
    Eb_I_sec(:,dloop)=Eb_I_sec_temp_sum/N;
else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
    Eb_I_sec(:,dloop)=Eb_I_sec_temp;
end

```

```

dloop=dloop+1;
end
figure(1)
plot(1:1:M,Eb_I_sec);
%legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
% hold
% plot(1:1:M,Pt_sec_dbm_max,'--');

legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Eb/I at secondary receiver');
%Pt_sec_max

```

### Code used to generate Figures 20-27

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
%for d_sec_bts = 1:2:8; %km
for d_sec_sec =0.2:0.2:0.8
d_sec_bts =4;%km
%d_sec_sec = 1.2;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);
for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);

```

```

Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec=25;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;
Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

% Pt_sec_sec_temp_dbm=zeros(1,N);
% d_sec_allowed_temp=zeros(1,N);

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

%
% scatter([sec_tx_x,0],[sec_tx_y,0],'red');
% scatter(sec_rx_x,sec_rx_y, 'green');
%
% plot(R*cos([0:0.1:2*pi]),R*sin([0:0.1:2*pi]));

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

```

```

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_temp = 10^(Eb_I_sec/10);
%Eb_I_sec_temp(i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_temp*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
d_sec_allowed_temp(Mloop,i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
Mloop=Mloop+1;

end

%d_sec_allowed(Mloop,dloop)=sum(d_sec_allowed_temp)/length(d_sec_allowed_temp
);

end
%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
    d_sec_allowed_temp_sum=sum(d_sec_allowed_temp');
    d_sec_allowed(:,dloop)=d_sec_allowed_temp_sum/N;
    Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
    d_sec_allowed(:,dloop)=d_sec_allowed_temp;
end
dloop=dloop+1;
end
% figure(1)
plot(1:1:M,Pt_sec_sec_dbm);
% legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
% hold
% plot(1:1:M,Pt_sec_dbm_max,'--');
%
%
% %legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
% xlabel('Number of active MSs in the cell');
% ylabel('Power transmitted by secondary TX to maintain Eb/I=20dB');
% %Pt_sec_max

%figure(2)
%plot(1:1:M,d_sec_allowed, 1:1:M,8*ones(1,length([1:1:M])), '--');
%legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');

```

```

legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Minimum distance between BTS and secondary transmitter');
% %Pt_sec_max

```

### Code used to generate Figure 28-35

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
%for d_sec_bts = 1:2:8; %km
for d_sec_sec = 0.2:0.2:0.8
d_sec_bts = 4;%km
%d_sec_sec = 1.2;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);
for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

```

```

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec=10;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;
Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

% Pt_sec_sec_temp_dbm=zeros(1,N);
% d_sec_allowed_temp=zeros(1,N);

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

%
% scatter([sec_tx_x,0],[sec_tx_y,0],'red');
% scatter(sec_rx_x,sec_rx_y, 'green');
%
% plot(R*cos([0:0.1:2*pi]),R*sin([0:0.1:2*pi]));

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_temp = 10^(Eb_I_sec/10);

```

```

%Eb_I_sec_temp(i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_temp*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
d_sec_allowed_temp(Mloop,i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
Mloop=Mloop+1;

end

end

%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
    d_sec_allowed_temp_sum=sum(d_sec_allowed_temp');
    d_sec_allowed(:,dloop)=d_sec_allowed_temp_sum/N;
    Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
    d_sec_allowed(:,dloop)=d_sec_allowed_temp;
end
dloop=dloop+1;
end
figure(2)
plot(1:1:M,d_sec_allowed, 1:1:M,8*ones(1,length([1:1:M])), '--');
%legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Minimum distance between BTS and secondary transmitter to maintain
Eb/I=10dB at secondary receiver');
% %Pt_sec_max

```

### Code used to generate Figures 36-51

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=450; %Mhz
hm=2; %m
hb=100; %m
hb_sec=10; %m
hb_sec_rx=2;
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
%for d_sec_bts = 1:2:8; %km
for d_sec_sec =0.2:0.2:0.8
d_sec_bts =4;%km

```

```

%d_sec_sec = 1.2;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);
for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec=10;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;
Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

```

```

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

%
% scatter([sec_tx_x,0],[sec_tx_y,0],'red');
% scatter(sec_rx_x,sec_rx_y, 'green');
%
% plot(R*cos([0:0.1:2*pi]),R*sin([0:0.1:2*pi]));

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_temp = 10^(Eb_I_sec/10);
%Eb_I_sec_temp(i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_temp*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
d_sec_allowed_temp(Mloop,i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
Mloop=Mloop+1;

end

%d_sec_allowed(Mloop,dloop)=sum(d_sec_allowed_temp)/length(d_sec_allowed_temp
);

end
%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
d_sec_allowed_temp_sum=sum(d_sec_allowed_temp');
d_sec_allowed(:,dloop)=d_sec_allowed_temp_sum/N;
Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');

```

```

    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
    d_sec_allowed(:,dloop)=d_sec_allowed_temp;
end
dloop=dloop+1;
end
figure(1)
plot(1:1:M,Pt_sec_sec_dbm);
xlabel('Number of active MSs in the cell');
ylabel('Power transmitted by secondary TX');

figure(2)
plot(1:1:M,d_sec_allowed, 1:1:M,8*ones(1,length([1:1:M])), '--');
%legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Minimum distance between BTS and secondary transmitter to maintain
Eb/I=25dB');

```

### Code used to generate Figures 52-61

```

close all;
clear all;
Pt_ms=316*10^-3; %Watt
%Path loss model : Ohumura-Hata
fc=880; %Mhz
hm=2; %m
hb=40; %m
hb_sec=2; %m
ahm=3.2*(log10(11.75*hm))^2-4.97;
dloop=1;
for d_sec_bts = 1:2:8; %km
%for d_sec_sec =0.2:0.2:0.8
%d_sec_bts =4;%km
d_sec_sec = 1.2;%km
R=8;%km

N=200;
for i=1:N
clear MS_pos_r MS_pos_a;
Mloop=1;
Sec_tx_a = rand(1,1)*2*pi;

Sec_rx_a= rand(1,1)*2*pi;

% scatter(MS_pos_r.*cos(MS_pos_a),MS_pos_r.*sin(MS_pos_a))
%
% hold
sec_tx_x=d_sec_bts*cos(Sec_tx_a);
sec_tx_y=d_sec_bts*sin(Sec_tx_a);

sec_rx_x=sec_tx_x+d_sec_sec*cos(Sec_rx_a);
sec_rx_y=sec_tx_y+d_sec_sec*sin(Sec_rx_a);

```

```

for M=1:1:200

Lp_ms_bts=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(R)-
13.82*log10(hb)-ahm;

Pr_bts_ms=Pt_ms/10^(Lp_ms_bts/10);
Pr_bts_ms_dbm=10*log10(Pr_bts_ms/10^-3);

Bw=5000; %khz;
Rate=9.6;% kbps
vf=0.4;
Gp=Bw/Rate;

%finding the max number of MS

f=0.67;
nc=0.8;
Eb_I=7;
Eb_I_sec=20;%db
%
Isec=Gp*Pr_bts_ms/10^(Eb_I/10)-Pr_bts_ms*(M-1)*(1+f)*vf*nc;
fsec=0.5;
Pr_bts_sec=Isec/fsec;
if (Pr_bts_sec < 0)
    Pr_bts_sec=0;
end
Pr_bts_sec_dbm = 10*log10(Pr_bts_sec/10^-3);
Lp_bts_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(d_sec_bts)-
13.82*log10(hb)-ahm;
Pt_sec_dbm_max(Mloop,dloop)=Pr_bts_sec_dbm+Lp_bts_sec;

Pt_sec_sec_temp_dbm=zeros(1,N);
d_sec_allowed_temp=zeros(1,N);

MS_pos_r(1,Mloop)=rand(1,1)*R;
MS_pos_a(1,Mloop)=rand(1,1)*2*pi;
MS_pos_x=MS_pos_r.*cos(MS_pos_a);
MS_pos_y=MS_pos_r.*sin(MS_pos_a);

Lp_bts_ms=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb))*log10(MS_pos_r)-
13.82*log10(hb)-ahm;
Pt_ms_active=Pr_bts_ms_dbm+Lp_bts_ms;

```

```

d_ms_sec= sqrt((MS_pos_x-sec_rx_x).^2+(MS_pos_y-sec_rx_y).^2);
Lp_ms_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_ms_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_ms_dbm=Pt_ms_active-Lp_ms_sec;

Pr_sec_ms=10^(-3)*10.^(Pr_sec_ms_dbm/10);
Eb_I_sec_temp = 10^(Eb_I_sec/10);
%Eb_I_sec_temp(i)=10*log10(Gp*Pr_sec_sec/(sum(Pr_sec_ms)*(1+f)*vf*nc));
Pr_sec_sec_temp=Eb_I_sec_temp*(sum(Pr_sec_ms)*(1+f)*vf*nc)/Gp;
Lp_sec_sec=69.55+26.16*log10(fc)+(44.9-6.55*log10(hb_sec))*log10(d_sec_sec)-
13.82*log10(hb_sec)-ahm;

Pr_sec_sec_temp_dbm=10*log10(Pr_sec_sec_temp/10^-3);
Pt_sec_temp_dbm(Mloop,i)=Pr_sec_sec_temp_dbm+Lp_sec_sec;
%Pt_sec_sec_temp(i)=10^(-3)*10^(Pt_sec_sec_temp_dbm(i)/10);
Lp_sec_bts_allowed= Pt_sec_temp_dbm(Mloop,i)-Pr_bts_sec_dbm;
Mloop=Mloop+1;
%d_sec_allowed_temp(i)= 10.^((Lp_sec_bts_allowed-69.55-
26.16*log10(fc)+13.82*log10(hb)+ahm)/(44.9-6.55*log10(hb)));
end

%d_sec_allowed(Mloop,dloop)=sum(d_sec_allowed_temp)/length(d_sec_allowed_temp
);

end
%Pt_sec_sec_dbm(:,dloop)=sum(Pt_sec_temp_dbm(Mloop,:))/N;
if(N>1)
    Pt_sec_temp_dbm_sum=sum(Pt_sec_temp_dbm');
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm_sum/N;
else
    Pt_sec_sec_dbm(:,dloop)=Pt_sec_temp_dbm;
end
dloop=dloop+1;
end
figure(1)
plot(1:1:M,Pt_sec_sec_dbm);
legend('d_sb=1km','d_sb=3km','d_sb=5km','d_sb=7km');
hold
plot(1:1:M,Pt_sec_dbm_max,'--');

%legend('d_ss=0.2km','d_ss=0.4km','d_ss=0.6km','d_ss=0.8km');
xlabel('Number of active MSs in the cell');
ylabel('Power transmitted by secondary TX to maintain Eb/I=25dB');

```

## BIBLIOGRAPHY

- [1].”Dynamic Primary-Secondary Spectrum Sharing with Cellular Systems”, Rathapon Saruthirathanaworakun, Jon M.Peha, Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM), 2010 Proceedings of the Fifth International Conference on , June 2010
- [2] Federal Communications Commission, “Spectrum Policy Task Force Report,” ET Docket No. 02-135, Nov. 2002
- [3] Cognitive Radio: “An integrated agent architecture for software defined radio”, J. Mitola III Doctor of Technology, Royal Institute of Technology, KTH, Sweden, May 2000.
- [4] “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey” Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran \*, Shantidev Mohanty, Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States, **Computer Networks** ,Volume 50, Issue 13, 15 September 2006, Pages 2127-2159
- [5] Federal Communications Commission, “Notice of Inquiry and Notice of Proposed Rulemaking”, ET FCC -ET Docket No. 03-289, Nov.2003
- [6] “Opportunistic use of 3G uplink licensed band”, Paulo Marques and Atilio Gameiro Communications, 2008. ICC '08. IEEE International Conference,19-23 May 2008
- [7] “Handbook of CDMA System Design, Engineering and optimization”, edited by Kyoung Il Kim, Upper Saddle River, NJ, Prentice Hall PTR, 2000, 2000 - csa.com
- [8] “Wireless network evolution 2G to 3G”, Vijay K. Garg , 1st Prentice Hall PTR Upper Saddle River, NJ, USA ©2001 ISBN:0130280771
- [9] ”Introduction to CDMA Wireless Communications” , Mosa Ali Abu-Rgheff, Published by Elsevier Ltd, 2007 ,ISBN: 978-0-75-065252-0