User Mobility Characterization in Mobile Cellular Systems with Differentiated Quality Coverage Zones

Vázquez Á. José L., Cruz P. Felipe A., Sánchez L. Rafael and Méndez M. Francisco

***Abstract*— In this paper user mobility characterization in mobile cellular systems with differentiated quality zones, distinguished by different Signal-to-Interference Ratios (SIRs), is carried out. In particular, we study the probability that a user in the bad quality zone of a cell moves into the good quality zone of the cell. This probability is of paramount importance to analyse the performance of mobile cellular systems with differentiated quality zones which has been erroneously calculated in previous works. Numerical results show that the probability that a user in the bad quality zone of a cell moves into the good quality zone of the cell is highly sensitive to the mobility model and to the previous path the user has followed.**

***Index Terms*—** *Mobile communication, mobility modelling, random walk, link adaptation, reuse partitioning.*

I. INTRODUCTION

Several resource allocation strategies have been proposed for mobile cellular systems with differentiated quality zones (in terms of the Signal-to-Interference Ratio -SIR-). These include Reuse Partitioning (RP) [1], Channel Borrowing Without Locking (CBWL) [2]-[3] and, Intelligent Underlay-Overlay (IUO) [4]. Physical layer improvements have also been proposed for these types of systems to increase their capacity [5]-[7]. The improvements have resulted in new speech/channel coding and modulation techniques as well as link adaptation (LA) and incremental redundancy (IR) techniques that can be combined depending on the communication channel conditions[1].

Reuse Partitioning (RP) is a technique that uses multiple reuse factors in the same cellular system. The main objective of RP is to provide an increase in system capacity over the capacity achievable with a single reuse factor, without relaxing SIR performance requirements. The underlaying principle behind RP is to degrade SIR performance for the mobiles that already have more than adequate transmission quality while offering greater protection to those mobiles that require it. The goal is to produce an overall SIR distribution that satisfies reception quality constraints while bringing about a general increase in system capacity. The available channels are split among several reuse patterns with different reuse factors. Mobile units with the best received signal quality will be preferentially assigned to the group of channels having the smallest reuse factor, while those with the poorest received signal quality will be only assigned to the group of channels having the largest reuse factor value.

CBWL is a family of channel assignment and sharing methods for cellular communications [2]-[3]. As in Fixed Channel Assignment (FCA), each cell is assigned a group channels (nominal channels) which are reused at cells that are sufficiently distant for the co-channel interference to be tolerable. In CBWL, if all nominal channels of a cell are occupied when a call arrives, channels can be borrowed from the neighbors. Channels can be borrowed only from an adjacent cell and are used with reduced transmitted power such that co-channel interference caused by channel borrowing is not worse than that of a non-borrowing scheme. The borrowed channels can be accessed only in part of the cell. To determine whether a MS is in the region that can be served by a borrowed channel, each cell transmits a Borrowed Channel Sensing Signal (BCSS) with the same reduced power as that on a borrowed channel. If the BCSS is above suitable threshold at a MS, a borrowed channel can be used by the MS. Thus, there are two zones in a cell: a zone where borrowed channels can be used and a zone where borrowed channels cannot be used.

Another possible way of improving capacity of cellular networks is to use different combinations of speech/channel coding, depending on the communication channel conditions. Such an approach has recently received lots of interest and has driven the development of Adaptive Multi-Rate (AMR) codecs family [8]. In AMR there are eight different speech/codecs with bit rates ranging from 4.75 to 12.2 kbps. Each speech codec can be used for voice transmission over a full-rate or half-rate channel depending of link quality. The channel model (FR/HR) can be switched (using Link Adaptation) in order to increase channel capacity by accommodating two HR users in one FR channel [5]-[6]. Actually, link adaptation (adaptive modulation and coding, and hybrid automatic repeat request, etc.) is one of the important techniques proposed to achieve 10 Mbps high date rate in 3GPP/3GPP2 specs.

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[1] The combination of these techniques has received a lot of attention recently and has driven the development of Adaptive Multi-Rate codecs family [8].

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In IUO, the frequency band is divided into two groups, a super layer with a small reuse factor and a regular layer with larger reuse factor. Thus a smaller coverage area is assigned to the super layer [4]. The origin of IUO principle was RP. It implements a two-layer network structure with a different reuse factor for each layer. The principle of IUO is to make use of the measurements carried out by the mobile station (MS). The MS always measures the strongest neighbors of the serving cell and determines when to make a handover to a neighbor cell. This measurement data is used to estimate the SIR conditions of the MS. If the estimated SIR is good enough, the MS is assigned a (heavily reused) so-called super frequency, while if the SIR is bad a regular frequency is assigned to the MS. In this way, the super frequencies can be used by mobiles with good SIR ratio, while the regular frequencies can be used over the whole cell.

Although the aforementioned strategies differ in the way they are implemented, they have similar mathematical abstraction. Their teletraffic performance in systems with differentiated quality zones can be analysed through the use of multi-dimensional Markov models. The events that can change the state of cells (driving process) in these systems are the same: new call arrivals in the different quality zones, inter-cellular and intra-cellular handoff attempts, and call termination. The state transition rates are determined by the new call arrival rate in the different quality zones, the quality zone residence times, and the service time. In order to make the analysis tractable, all these quantities are commonly assumed to be negative exponentially distributed random variables [3]-[7], [9].

Intra-cellular handoffs are an important distinguishing feature of mobile cellular systems with differentiated quality zones. For example, in a system with two quality zones, each user can move freely throughout the system and it can leave its current quality zone. Typically, it is assumed that a user in the good quality zone of a cell can move only into the bad quality zone of the cell. However, a user in the bad quality zone of a cell can move either into the good quality zone of the cell or into the bad quality zone of an adjacent cell. To fully specify mobile cellular systems with differentiated quality zones, it is necessary to know the probability, q, that a user located in the bad quality zone moves into the good quality zone or enters the bad quality zone of an adjacent cell (with probability 1-q).

Although different mobility-related parameters (i.e., channel holding time, cell boundary crossing rate, cell residence time) in cellular systems have been widely studied in the literature [10], [11], the parameter q in mobile cellular with differentiated quality zones has not received sufficient attention so far. A literature survey shows that relatively few in-depth papers have been published on this subject [2]-[3]. In [2]-[3], Jiang et al derived an expression for the probability q in terms of the fraction of the area with good quality links. However, as it will be shown, this expression yields unsound results. An accurate user mobility modelling will facilitate the performance assessment of link adaptation in cellular systems, specially those with 3G technology.

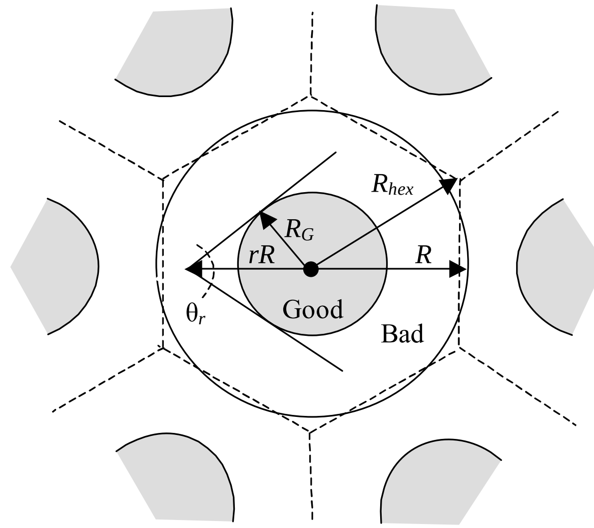

Fig. 1. Cellular system with differentiated quality zones.

In this paper, we derive new expressions to calculate the probability that users in the bad quality zone of a cell move into the good one (q). The expressions are validated by computer simulations and compared to the expression reported in [2]-[3]. Numerical results for two different user mobility models show that the probability q is a monotonically increasing function of the fraction of the cell area with good quality links as opposed to a parabolic dependence as reported in [2]-[3].

II. System Model and Previous Related Work

A homogeneous mobile cellular system with omni-directional antennas located at the centre of cells is assumed. Each cell is circular with radius R (calculated such that the area of the circle has the same area of a hexagonal cell with radius R_{hex}). Inside each cell, two coverage zones differentiated by signal quality exist. As in [1]-[5], no shadowing is considered. Then, since the received power is a function of the distance only [9], the quality zones are concentric circles. The inner (outer) zone is referred to as the good (bad) quality zone. Thus, the good quality zone is formed by the inner circle with radius R_G, and the bad quality zone is that cell area not covered by the good quality zone, as shown in Figure 1.

A parameter, p, is used to represent the proportion of users that request service in the good quality zone (the calculation of p considering shadowing is addressed in [6]). In [2]-[3], q has been expressed in terms of p as follows:

$$q = \frac{(1-p)p^z}{1+(1-p)p^z} \tag{1}$$

Where the parameter z is determined by the mobility characteristics of the mobile users. [2] and [3] state that when z = 1, mobile users move randomly and the mean dwell time in the good quality zone is directly proportional to the fraction of the good quality zone's area. On the other hand, when z = 0.5, mobile stations move in straight lines with constant direction. Notice that as p tends to one, q tends

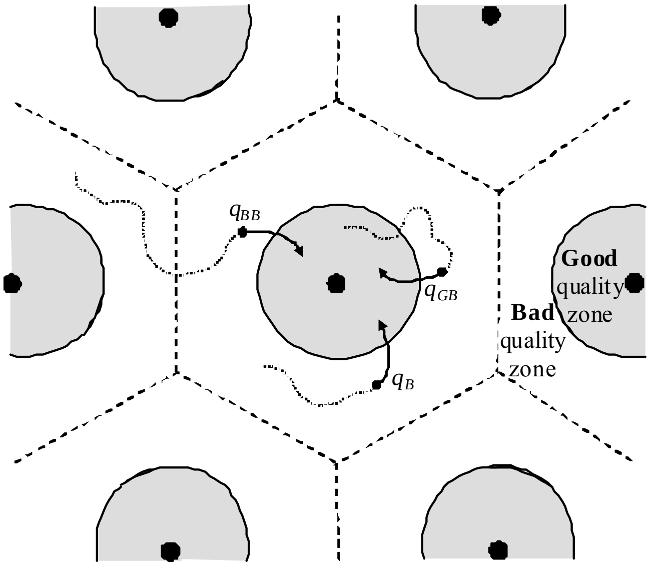

Fig. 2. Different conditional probabilities that users in the bad quality zone of a cell move into the good quality zone of the cell.

to zero in equation (1). This means that as the coverage area of the good quality zone increases the probability that a user in the bad quality zone of a cell moves into the good quality zone of the cell decreases. This is unreasonable because as the coverage area of the good quality zone increases, clearly, the possibility that the users get into that zone increases. This has motivated us to analyse the probability q.

III. Analysis of the Probability that a User Moves from the Bad to Good quality Zone

In this section analytical expressions are obtained for the probability that a user in the bad quality zone of a cell moves into the good one (q), considering two different user mobility models: a simplified model and a generalised model.

A. Simplified Mobility Model

This model assumes that mobiles are uniformly distributed in the system and that mobiles move in straight lines with random direction uniformly distributed between $[0, 2\pi)$. Instantaneous speed varies continuously but, like the residence time, it is of little interest for this model. The probability that a user (mobile) enters into the good quality zone of a cell depends on the zone the mobile is traversing before entering. This results in three different cases of analysis for the probability q, described below.

These cases are (see Figure 2): the conditional probabilities that users in the bad quality zone of a cell move into the good quality zone given that: 1) users originate their calls in the bad quality zone (q_B), 2) users arrived to the bad quality zone coming from the good quality zone (q_{GB}), and 3) users arrived to the bad quality zone coming from the bad quality zone of another cell (q_{BB}).

1) *Users that originate their calls in the bad quality zone*

Here, our objective is to calculate the conditional probability that a user in the bad quality zone of a cell moves into the good one given that users originate their calls in the bad quality zone (q_B), hence we are only interested in those users that are in the bad quality zone. The system is assumed to be homogeneous, hence, only one cell needs to be analysed. Since users are uniformly distributed throughout the cell, the proportion of users in the good quality zone, p, can be calculated as a function of the total cell area and the good quality zone area as follows:

$$p = \frac{\pi R_G^2}{\pi R^2} = \left(\frac{R_G}{R}\right)^2 \tag{2}$$

Let us now assume that a user is located at a distance rR from the centre of the cell (with $R_G/R \leq r \leq 1$). The probability that the user moves into the good quality zone, q, is the probability that the user moves within a certain range of directions determined by the angle θ_r (which is shown in Figure1)[2]. From Fig. 1, it can be observed that:

$$\sin\left(\frac{\theta_r}{2}\right) = \frac{R_G}{rR} \tag{3}$$

And therefore,

$$\theta_r = 2\arcsin\left(\frac{R_G}{rR}\right) \tag{4}$$

Due to the uniformly distributed random direction assumed, the probability that a user located in the bad quality zone of a cell moves into the good quality zone of the cell (event A) given that the user is located in the bad quality zone at a normalised distance r from the centre of the cell, $P(A|r)$, is given by:

$$P(A|r) = \frac{\theta_r}{2\pi} = \frac{1}{\pi}\arcsin\left(\frac{R_G}{rR}\right) \tag{5}$$

Using the total probability theorem (averaging over all the points in the bad quality zone) we can find q_B, as follows:

$$q_B = \frac{1}{\pi(1-p)}\int_0^{2\pi}\int_{R_G/R}^{1} P(A|r)\, r\, dr\, d\theta \tag{6}$$

Using (2) and (5), q_B can then be expressed as follows:

$$\begin{aligned} q_B &= \frac{1}{\pi(1-p)}\int_0^{2\pi}\int_{\sqrt{p}}^{1} \frac{1}{\pi}\arcsin\left(\sqrt{p}/r\right) r\, dr\, d\theta \\ &= \frac{1}{\pi(1-p)}\left[-\frac{p\pi}{2} + \sqrt{p(1-p)} + \arcsin\left(\sqrt{p}\right)\right]; 0 \leq p < 1 \end{aligned} \tag{7}$$

2) *Users that arrive in to the bad quality zone of a cell coming from the good quality zone of the same cell*

In this case we assume that users in the bad quality zone come from the good quality zone of the same cell. That is, it is assumed that a user moves out of the good quality zone

[2] Given a normalised distance r, the angle θ_r can always be represented by two straight lines tangent to the circle of radius R_G.

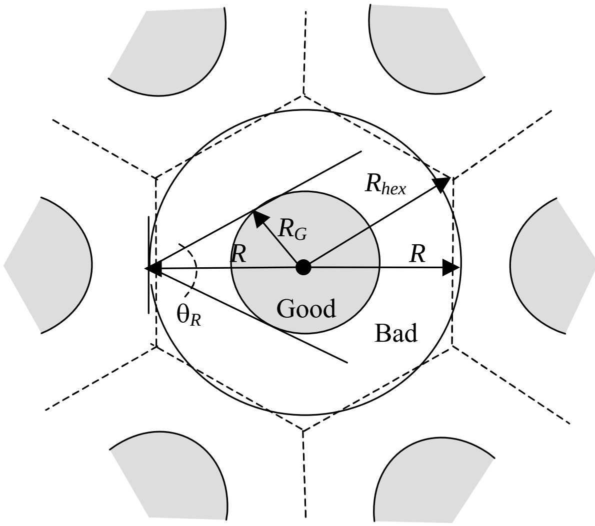

Fig. 3. Cellular system with differentiated quality zones for case 3.

toward the bad quality zone of the same cell and then, once the user has entered to the bad quality zone, it returns to the good quality zone of the same cell with probability q_{GB}. This probability depends strongly on the randomness of the user´s direction. In fact, when the user´s direction does not change the probability that a user returns to the good quality zone is zero (that is, q_{GB} =0). Random movement is considered in next sub-section.

3) *Users that arrive in to the bad quality zone of a cell coming from the bad quality zone of another cell*

As in [12], in this case we consider that users can enter into the cell by crossing any point of the cell boundary. We consider a circle-shaped cell with radius R, such that the cell area is the same as that of a hexagon with radius R_{hex}, as in [12]. In order to facilitate the analysis we further assume that users arriving into the bad quality zone coming from another cell cross the cell boundary with a direction uniformly distributed between (-π/2, π/2) relative to the radial line. In this case our objective is to find the probability that a user gets into the good quality zone, which is equivalent to find the probability that a user moves with an angle between ($-\theta_R/2$, $\theta_R/2$)., see Figure 3. Then, from Figure 3 we can observe that

$$\sin\left(\frac{\theta_R}{2}\right) = \left(\frac{R_G}{R}\right) \qquad (8)$$

with (2) and solving for θ_R, we have

$$\theta_R = 2\arcsin\left(\sqrt{p}\right) \qquad (9)$$

Due to the uniformly distributed random direction assumed, the probability that a user located in the boundary of the cell moves into the good quality zone of the cell, q_{BB}, is given by

$$q_{BB} = \int_{-\frac{\theta_R}{2}}^{\frac{\theta_R}{2}} \frac{d\alpha}{\pi} = \frac{\theta_R}{\pi} = \frac{2}{\pi}\arcsin\left(\sqrt{p}\right) \qquad (10)$$

This last expression is true, since each user located on the boundary of the cell (on the perimeter of the circle) has the same probability to enter into the good quality zone.

In [13], it is shown that the speed and direction distributions of the in-cell mobiles are different from those of the cell-boundary crossing mobiles (users that originated calls in neighbouring cells that are handed off into the cell under study). Let $f(\alpha)$ be the probability density functions (pdf) of the directions of all mobile stations, which is uniformly distributed in the range (0, 2π). Based on the biased sampling, the pdf of the directions of the cell-boundary crossing terminals $f^*(\alpha)$ can be obtained as ([10] and [13]):

$$f^*(\alpha) = \begin{cases} \frac{1}{2}\cos(\alpha); & -\frac{\pi}{2} \le \alpha \le \frac{\pi}{2} \\ 0 & ;\ \text{otherwise} \end{cases} \qquad (11)$$

α is the angle relative to the radial line by which the user enters to the cell. Considering this pdf for the direction of the cell-boundary crossing terminals, it is possible to find the probability that handed off users enter into the good quality zone of the cell under study. Once again, we will assume that users cross the perimeter of the circular cell with radius R (see Figure 3). Users that cross the boundary follow a random direction relative to the radial line with a pdf given by (11). As in the previous case, the probability that a user gets into the good quality zone is the same as the probability that a user crossing direction takes an angle between ($-\theta_R/2$, $\theta_R/2$) (see Figure 3). Hence θ_R is given by (9). Considering (11) and using (9), the probability that a user in the bad quality zone of a cell moves into the good quality zone of the cell with biasing in the direction of the boundary crossing mobiles, q_{BB}^*, is given by

$$q_{BB}^* = \int_{-\frac{\theta_R}{2}}^{\frac{\theta_R}{2}} f^*(\alpha)d\alpha = \int_{-\frac{\theta_R}{2}}^{\frac{\theta_R}{2}} \frac{1}{2}\cos(\alpha)d\alpha = \sin\left(\frac{\theta_R}{2}\right) = \sqrt{p} \qquad (12)$$

B. Generalised Mobility Model

Equations (7), (10), and (12) represent the probability that users in the bad quality zone of a cell moves into the good quality zone for the simplified mobility model in which there is no change in the direction of movement. In a general case, not only should the mobility model include changes in the speed of the mobile but in the direction (it is unrealistic to assume that the direction remains constant). However, it is virtually impossible to extend the mathematical analysis of the simplified case to cover the general case of mobility, and simulation offers the only way to model it. Computer simulations can be developed to study mobility under generalised assumptions. For the simulations, we consider the random walk mobility model of [10]. The assumptions include: 1) independent users uniformly distributed over the entire system, 2) mobiles are allowed to move away from the starting point in any direction with equal probability, 3) users move in a straight line with constant speed and direction along a given distance interval, 4) the probability

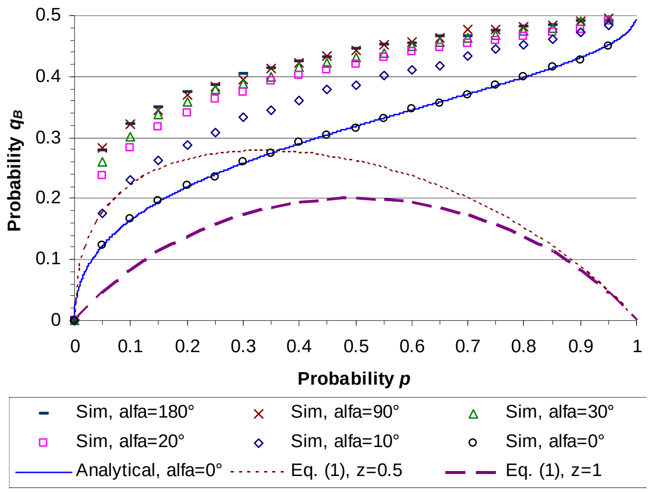

Fig. 4. Conditional probability that users in the bad quality zone of a cell move into the good one given that users originate their calls in the bad quality zone, q_B, versus the proportion of users that request service in the good quality zone with the angle α as parameter.

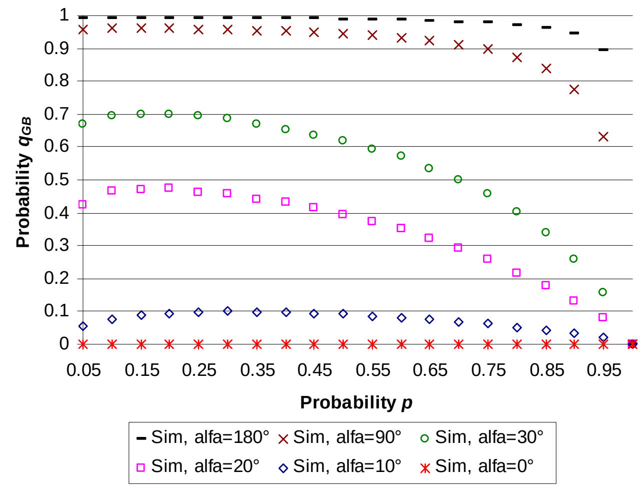

Fig. 5. Conditional probability that users in the bad quality zone of a cell move into the good one given that users arrived to the bad quality zone coming from the good quality zone, q_{GB}, versus the proportion of users that request service in the good quality zone with the angle α as parameter.

of the variation of the mobile direction along its path is a uniform distribution limited in the range of ±α relative to the current direction, 5) the initial velocity of the mobile stations is a random variable with Gaussian probability density function truncated in the range (0, 100 km/h), and 6) the velocity increment of each mobile is a uniformly distributed random variable in the range ±10% of the current velocity. Notice that the generalised mobility model with α =0° is equivalent to the simplified mobility model.

IV. Numerical Results

In this section both analytical and simulation results are compared. In the simulations, 50,000 independent users are uniformly generated in each of the cases as follows: 1) users are generated on the bad quality zone of the cell under study, 2) users are generated on the good quality zone under study, and 3) users are generated on the perimeter of the cell under study. Cell radius, *R*, is assumed to be 5 km. The mobility model assumes that users move in a straight line with constant speed and direction along a length of 20 m [14]-[15]. α is varied in order to get the performance of *q* for different degrees of mobility randomness.

Figure 4 shows the curves for *q* obtained with the Jiang's expression given by eq. (1), labelled "Eq. (1)", plotted against the probability *p* (fraction of the cell area with good quality links). Two cases are shown for that expression: z =0.5 and z = 1. According to [3] and [5], the former case corresponds to our simplified mobility model or to our generalised mobility model with α = 0°. The latter corresponds to the case where users move randomly (α = 180° in the generalised mobility model). Notice that, with Jiang's expression, *q* as function of *p* has a parabolic form and as *p* tends to one, *q* tends to zero. This is unreasonable because, clearly, as the coverage area of the good quality zone increases, the possibility that the users get into that zone should increase. In fact, in the limit, when *p* tends to 1, users in the bad quality zone of a cell have an almost equal chance to move into the good quality zone or into the bad quality zone of an adjacent cell and, therefore, *q* must tend to 0.5 instead of tend to zero. Additionally, Jiang's expression suggests that, for a given value of *p*, the corresponding value of *q* is smaller for the case where users move randomly than that for the case where users move in straight lines. This is also incorrect, as it will be explained below.

Figure 4 also shows the conditional probability q_B obtained with equation (7) as a function of the parameter *p*. Analytical results, given by equation (7), and simulation results are shown for the simplified mobility model. They are labelled, respectively, "Analytical, alfa=0°" and "Sim, alfa=0°". Also, results are shown for the simulations carried out for the generalised mobility model (evaluated for different values of α and labelled "Sim, alfa={0°, 10°, 20°, 30°, 90°, and 180°}"). Note that analytical and simulation results for the simplified mobility model agree perfectly. In contrast to the parabolic form of equation (1), our results (curves other than those labelled "Eq. (1)") show that the probability *q* is a monotonically increasing function of the fraction *p* of the cell area with good quality links. It can be observed that the minimum (maximum) value of *q* is obtained when *p* is 0 (1). Also, in contrast to what is suggested by Jiang [3], it is observed that for a given *p*, as α increases (and, therefore, the movement randomness) *q* also increases. That is, the more random user mobility is, the larger *q* becomes. However, for a given *p*, with values of α larger than 90°, *q* remains almost constant. Since mobility patterns in real cellular systems depend heavily on the topology, then it is expected that, for a given value of *p*, *q* takes smaller values in macro-cellular environments than in micro-cellular environments.

Figure 5 shows the conditional probability q_{GB} for the case in which the users originate calls in the good quality zone. From this figure it can be observed that once the user has moved into the bad quality zone, the more random the direction of the mobile (the higher α is), the higher the

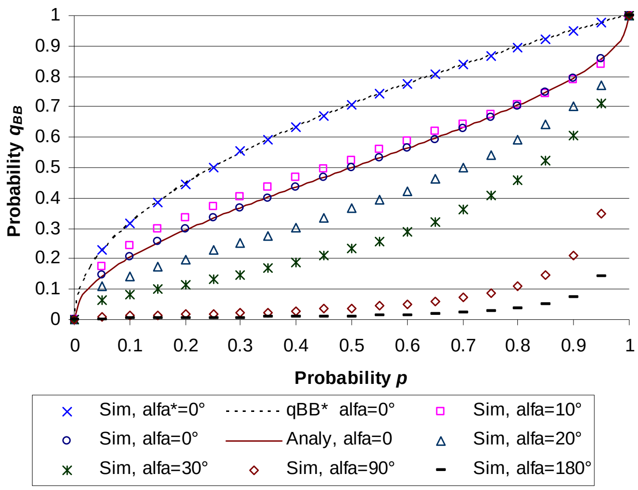

Fig. 6. Conditional probability that users in the bad quality zone of a cell move into the good one given that users arrived to the bad quality zone coming from the bad quality zone of another cell, q_{BB}, versus the proportion of users that request service in the good quality zone with the angle α as parameter.

probability of seeing that mobile returning into the good quality again, q_{GB}, is. That is logical because the higher α is, the more drastic the changes in the direction are and therefore, the higher the likelihood that the mobile will return into the good quality zone after doing few movements. As p increases the good quality zone boundary is closer to the cell boundaries and the higher the likelihood that users leave the cell without returning to the good quality zone. This effect is more notorious for small values of α, since the initial direction doesn't change drastically.

Figure 6 shows the conditional probability q_{BB}. From this figure, it can be observed that the probability that a user moves into the good quality zone of the cell is a monotonically increasing function of p. In this figure, both analytical and simulation results agree perfectly for the case where α=0°. As α increases, the probability q_{BB} increases too, except for α=10°. Notice that abrupt changes in mobile direction (i.e. more than 20° with respect to its current direction) result in mobiles moving out of the cell under study after a few movements. This is particularly true for large values of α. When α=10°, changes in mobile direction are not so drastic. Hence, mobiles move almost in a straight line. However, those changes are such that mobiles can often enter into the good quality zone. When p is large, the good quality zone boundary tends to the cell's boundary, and since mobiles movement is almost over a straight line, the probability that mobiles will move into the good quality zone is almost the same as in the case when α=0° as shown in Figure 6. Figure 6 also shows the probability q_{BB}^*, when we use the correction of the pdf for users that are handed off into the cell under study. This probability is labelled q_{BB}^*. The results obtained by simulation of this probability are labelled as "Sim, alfa*=0°". Both analytical and simulation results agree perfectly. The probability q_{BB}^* is larger than probability q_{BB} because handed off users with biasing in the direction of the boundary crossing tend to go towards the centre of the cell and, therefore, with higher probability enter to the good quality zone of the cell.

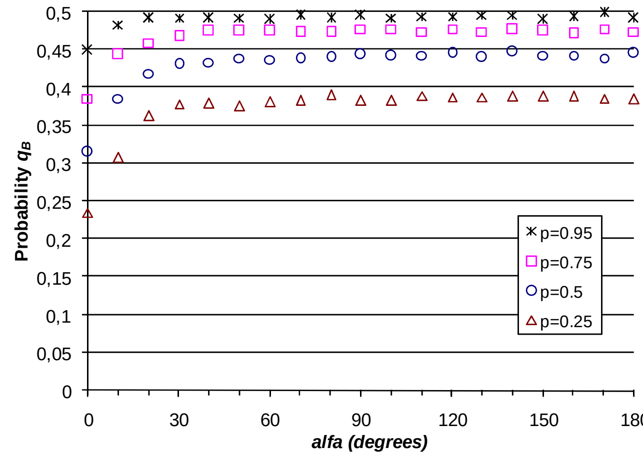

Fig. 7. Probability that users in the bad quality zone of a cell move into the good one versus the angle α with the proportion of users that request service in the good quality zone as parameter.

Finally, in Figure 7 we observe the behaviour of the probability that users that originate in the bad quality zone move into the good quality zone q_B, plotted versus the maximum change in the current direction, α. We can observe three different behaviours of q_B in the evaluation range. For values of α smaller than 30°, q_B shows a quick grow. For values between α=30° and α=90°, q_B shows a moderate grow. Finally, for values of α larger than 90°, q_B practically remains constant. Also, we can see that as p increases, q_B increases too.

V. Conclusions

We have derived a new expression for the probability that a user in the bad quality zone of a cell moves into the good quality zone, q, in mobile cellular systems with differentiated quality zones. For the numerical results, we considered two different user mobility models. Our results are totally different to those previously reported in the literature [2, 3]. It is important to note that our results are validated by the perfect agreement of analytical and simulation results for the simplified mobility model where users cannot change their direction of movement.

Comprehensive simulation results show that the probability that a user in the bad quality zone of a cell moves into the good quality zone of the cell is highly sensitive to the mobility model and to the previous path the user has followed. Then, for the teletraffic analysis of the mobile cellular systems with differentiated quality coverage zones, it is necessary to properly model the users' mobility. Probability q (q_B) can be used in order to calculate the intra-cellular handoff failure probability for those users that move from the bad to the good quality zone. In the analysis by multidimensional birth and death processes, it is necessary to utilize different state variables to represent the number of active users in each zone.

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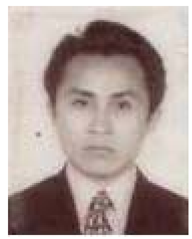

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