A Flexible Dynamic Traffic Model for Reverse Link CDMA Cellular Networks

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***Abstract*—In this paper, we focus on the reverse link traffic analysis of a code-division multiple-access (CDMA) cellular network in dynamic environments. In this respect, we propose a new and flexible traffic model, which takes into account the interference-limitedness attribute of CDMA capacity as well as its soft-handoff feature. This new traffic model is developed according to interference-based call admission control (ICAC) method and a geographical structure with three regions. The main advantage of this traffic model is in its flexibility when we consider different traffic conditions including time-varying status of traffic in the neighboring cells.**

***Index Terms*—Admission control, code-division multiple-access (CDMA), soft capacity, soft-handoff, traffic analysis, traffic model.**

I. Introduction

CODE-DIVISION multiple-access (CDMA) scheme plays a crucial role in third generation mobile systems. Universal mobile telecommunication system, UMTS, an important standard for third generation mobile system, is based on wide-band-CDMA (W-CDMA) as its multiple access technique [1]. CDMA has numerous attributes that distinguish it from other techniques such as time-division multiple-access (TDMA) and frequency-division multiple-access (FDMA). One of its distinct attributes is soft capacity which is due to its interference-limited behavior. This feature affects other aspects of CDMA cellular networks such as traffic analysis. Because of stochastic nature of interference, and thus capacity, we need a suitable method for admission control in traffic analysis.

Ishikawa and Umeda discussed two basic methods for call admission control [2]. For the first method, namely, number-based call admission control (NCAC), we have N number of channels. N should be determined according to the whole traffic status of the network. In this method, the resources of a network are equivalent to the number of channels. However, in the second method which considers interference-based call admission control (ICAC), the resources in the network are proportional to the level of interference. Hence, ICAC method appears to be more suitable with respect to the interference-limitedness attribute of CDMA capacity. In this method for admitting any new arrival, the current short-term interference is compared with a threshold. Furthermore, due to randomness of short-term interference the result of this comparison appears as an admission probability in ICAC method. Therefore, for ICAC method we do not have a restriction on the number of channels explicitly, however, transition rates diminish while the traffic states go into the higher and higher states.

The other key feature of a CDMA cellular network is its ability to employ soft-handoff scheme. In this scheme more than one base station (BS) coordinate amongst themselves to provide communication services for mobile stations (MS's) placed in their corresponding boundary regions. Thus, in fact, for soft-handoff scheme we have a transition band as opposed to a transition boundary (line) such as for hard-handoff scheme. Soft-handoff has numerous benefits in view of interference optimization, capacity, and QoS enhancement ([3]–[7]) and a few disadvantages in relation to forward link such as degradation in capacity [8]. The main feature for soft-handoff process reverts to power-control of the MS's by the best BS. Two important criteria in this respect are signal to interference ratio (SIR) and path loss (or equivalently, received pilot strength). Furthermore, because of a new type of region, i.e., soft-handoff region (SHR), formed by applying soft-handoff scheme, there are more options for designing traffic management algorithms and thus, more flexibility and accuracy in traffic modeling and analysis, respectively.

In general, traffic analysis is performed based on a traffic model that includes a typical region indicating a sample of the whole network. Traffic analysis can be performed for either immobile (users with no mobility) or dynamic (users with mobility) cases. The basic distinguishing feature of the latter, i.e., dynamic, is the handoff process. Some of the previously proposed traffic models for CDMA cellular networks, do not consider time-varying attribute of the traffic and they focus on static capacity [9] only, i.e., equally loaded cells without any handoff ([4], [10]–[12]). Others do not consider soft capacity feature of CDMA cellular network and consider the network capacity like non-CDMA cellular networks ([13], [14]). Furthermore, some base their traffic analysis for nondynamic case only, i.e., without considering mobility and handoff problem ([2], [9], [15]). Also, almost all of these previous traffic models incorporate traffic status of the neighboring cells as a stationary random variable, and do not consider its time-varying characteristics.

In this paper, we intend to propose a flexible and dynamic traffic model that is suitable for reverse link traffic analysis of CDMA cellular networks. In this model we employ ICAC method for soft capacity and we consider soft-handoff process in our geographical configuration. Flexibility of this new traffic model reverts to considering time-varying traffic status of the

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neighboring cells and thus, its ability to analyze heterogenous spatial traffic conditions more accurately when compared to previous traffic models. Also, this new traffic model is suitable in designing and comparing new traffic and especially handoff management algorithms with respect to soft-handoff process [16].

Following this introduction we will describe issues of a general traffic model in Section II, and will propose a new reverse link traffic model in Section III. We will conclude this paper in Section IV.

II. General Characteristics of a Traffic Model

Our main goal in proposing a traffic model is to provide means to analyze a CDMA cellular network in reverse link in view of evolutionary time-varying traffic for dynamic case (users with mobility) with emphasis in soft-handoff process. In this type of analysis increasing and decreasing the number of users are considered step by step. One of the most important traffic parameters which is obtained from this type of analysis is the carried traffic, that can be viewed as dynamic capacity of the system. In the literature, usually, the static capacity of the network is considered with the same number of users in all the cells ([4], [10]–[12]). Obviously, this cannot be a practical case with respect to traffic evolution. Even for the case of the same primary traffic parameters (such as arrival rate, average cell sojourn time, average call duration time, etc.) for all cells, we cannot deduce that the number of users is always the same in different cells. Thus, dynamic traffic analysis may lead to more practical results.

In general, typical dynamic traffic analysis of a cellular network is carried numerically and if one considers the whole network the order of computations may become very large. Thus, a viable approach for dynamic traffic analysis is to consider a small region representing a sample of the whole network and consequently extending the results to the whole network [17]. With respect to soft-handoff scheme this small region usually includes a cell (desired cell) and its neighboring overlap regions ([6], [13]). In general, we estimate some required traffic parameters related to the neighboring cells. For simplicity, we assume the same average traffic parameters, i.e., blocking and dropping probabilities, for the desired cell and its neighbors.

We can state that in a CDMA cellular network model we should make decisions with respect to two basic issues, first, the basic method of admission control and second, the geographical structure of the model with respect to soft-handoff. Obviously, our decision-based model should be such that it is flexible enough to facilitate the analysis for different traffic conditions and simple enough in order to be mathematically tractable. In fact, we need a suitable tradeoff between simplicity and flexibility. For example, a flexible geographical structure enables us to consider spatially heterogenous traffic conditions which in turn results in more complex traffic analysis.

Another important issue with respect to a traffic model is the corresponding probability distribution for primary traffic parameters such as new call generation process, cell sojourn time, call duration time, orientation in different directions, etc. The standard assumption that often simplifies the solution of the

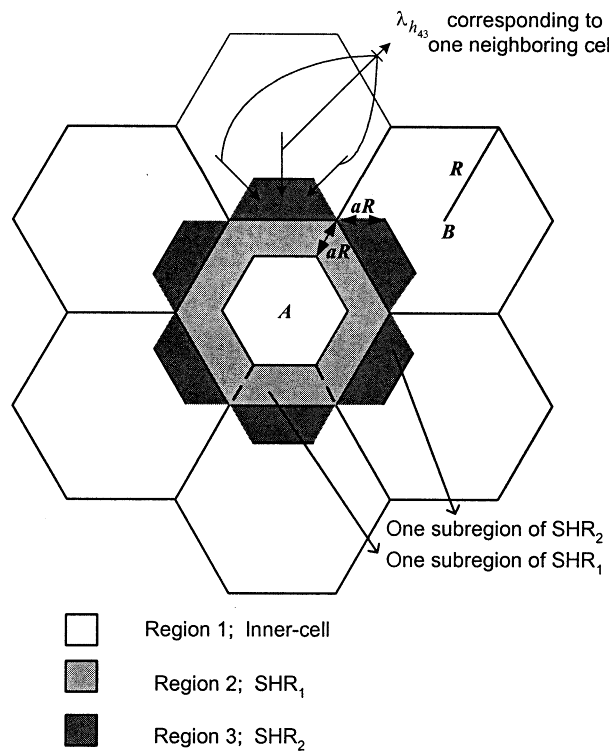

Fig. 1. Geographical structure of the proposed traffic model.

Markov chain corresponding to a traffic model is the memoryless property of the related distributions (like negative exponential distribution for inter-arrival time, cell sojourn time, and call duration time).

III. Proposed New Traffic Model

Our new model, which is based on ICAC method to include soft capacity, considers a desired cell (cell A) and its overlap regions (Fig. 1) in a macrocellular structure with nonsectorized cell sites. Due to its efficiency, we compute the related parameters based on a 3-cell soft-handoff scheme [4], [18], however, for the sake of simplicity, we consider only the two nearest cells to the desired cell A as the determining and decision-making BS's in SHR. This model divides the considered area into three regions (Fig. 1). The first region, inner-cell region, includes MS's that are power-controlled by cell A and do not communicate with any other base station. The second region (SHR_1) includes MS's that are placed in soft-handoff region and are power-controlled by cell A. And third region (SHR_2) includes the MS's in soft-handoff region that cell A is not their power-controlling BS.[1] In this model, we consider path loss (equivalent to pilot signal strength with the assumption of the same pilot strength at all BS's) as the criterion of power-control. And also, we assume the same target received power at the BS's corresponding to the desired cell and its neighboring cells. The motivation for this geographical structure is to be able to analyze the MS's with various interfering effects on cell A, which, will ultimately re-

[1]In fact due to shadowing, it is possible, in practice, that some of the MS's in SHR_2 are power-controlled by cell A and some of the MS's in SHR_1 are not power-controlled by cell A. However, with some minor modifications we are able to include the effect of shadowing in this partitioning.

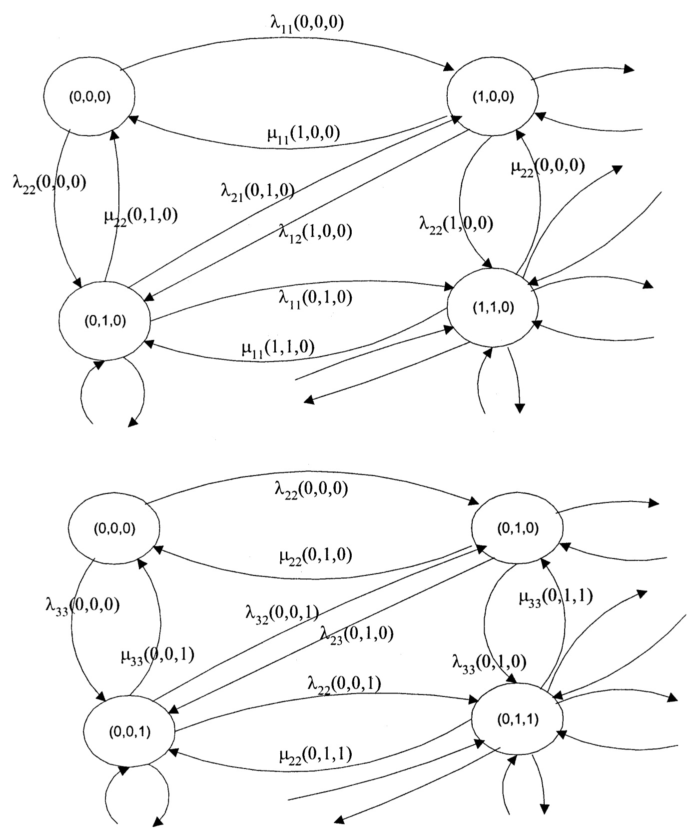

Fig. 2. Markov chain corresponding to the proposed traffic model.

sult in different treatment of the network on the corresponding MS's. In fact, when we consider the movement or the migration of an MS from inside a neighboring cell (such as cell B) toward cell A and crosses the edge of SHR, its interfering effect will become noticeable in cell A. However, MS's placed in SHR, have various interference effect on cell A. Obviously, an MS in SHR belonging to cell B, i.e., SHR_2, has less interference compared to ones belonging to cell A, i.e., SHR_1 . Note that, with the assumption of perfect power-control, MS's placed in SHR that are power-controlled by cell A (SHR_1) have the same interference effect on cell A as for MS's placed in inner-cell region. In this paper, we propose that for a CDMA cellular network, MS's should be treated differently according to their contributed interference level on cell A, hence, our geographical structure enables us to analyze different traffic management policies that have different treatment with respect to these two types of MS's in SHR.

In this model, we employ the standard assumption for primary traffic parameters. Hence, for the analysis of a traffic management algorithm based on the above traffic model we need to solve a 3-dimensional Markov chain as illustrated in Fig. 2. From this figure, (i, j, k) is the state of the Markov chain such that i, j, k are the number of users in first, second and third regions, respectively. Also, we use the following notation for the Markov chain equations corresponding to the proposed traffic model in general case:

$\lambda_{n_u}(u=1,2,3)$: New call origination rate in the region u;

$P_{B_u}(i,j,k)$: Blocking probability of a new call request in region u, at (i, j, k) traffic state;

μ_c : Inverse of average call duration time;

μ_{R_u} : Departure rate (due to mobility) from region u (inverse of sojourn time in region u);

$P_{tr_{uv}}$: Probability of an MS moving from one subregion of region u to another subregion of region v (inner-cell region has only one subregion);

$P_{D_{uv}}(i,j,k)$: Dropping probability while migrating from region u to region v at (i, j, k) traffic state;

$\lambda_{h_{43}}$: Migration rate from neighboring cells' regions (index 4) to SHR2 (index 3) of the traffic model (Fig. 1);

μ_{r_u} : Departure rate from one subregion of region u;

$P_{d_u}(i,j,k)$: Dropping probability of an MS while moving between two subregions in region u at (i, j, k) traffic state.

For the traffic analysis based on this model we should determine transition rates in the obtained Markov chain (Fig. 2). The related expressions, in general, can be written as in the following:

$$\lambda_{11}(i,j,k) = \lambda_{n_1}(1 - P_{B_1}(i,j,k)), \tag{1}$$

$$\mu_{11}(i,j,k) = i\mu_c + i\mu_{R_1}P_{D_{12}}(i,j,k), \tag{2}$$

$$\lambda_{22}(i,j,k) = \lambda_{n_2}(1 - P_{B_2}(i,j,k)), \tag{3}$$

$$\begin{aligned}\mu_{22}(i,j,k) = & j\mu_c + j\mu_{r_2}P_{tr_{23}}P_{D_{23}}(i,j,k) \\ & + j\mu_{r_2}P_{tr_{22}}P_{d_2}(i,j,k),\end{aligned} \tag{4}$$

$$\begin{aligned}\lambda_{33}(i,j,k) = & \lambda_{n_3}(1 - P_{B_3}(i,j,k)) \\ & + \lambda_{h_{43}}(1 - P_{D_{43}}(i,j,k)),\end{aligned} \tag{5}$$

$$\mu_{33}(i,j,k) = k\mu_c + k\mu_{r_3}P_{tr_{32}}P_{D_{32}}(i,j,k) + k\mu_{r_3}P_{tr_{34}}, \tag{6}$$

$$\lambda_{12}(i,j,k) = i\mu_{R_1}(1 - P_{D_{12}}(i,j,k)), \tag{7}$$

$$\lambda_{21}(i,j,k) = j\mu_{r_2}P_{tr_{21}}, \tag{8}$$

$$\begin{aligned}\lambda_{13} &= 0 \\ \lambda_{31} &= 0,\end{aligned} \tag{9}$$

$$\lambda_{23}(i,j,k) = j\mu_{r_2}P_{tr_{23}}(1 - P_{D_{23}}(i,j,k)), \tag{10}$$

$$\lambda_{32}(i,j,k) = k\mu_{r_3}P_{tr_{32}}(1 - P_{D_{32}}(i,j,k)). \tag{11}$$

We compute the arrival and departure rates corresponding to different regions, and the probabilities for moving in different directions, in Appendix A. Due to ICAC method for blocking probability of a newly originatined call and dropping probability due to handoff failure, at each traffic state, we need to compute the probability that current short-term interference level exceeds the corresponding thresholds. Interference is comprised of two parts; intra-cell and inter-cell, and both are stochastic in nature. With the assumption of perfect power-control, randomness of the first part, intra-cell, is due to intermittence such as voice activity factor or burstiness in data traffic. Intra-cell interference for the case of voice only is modeled by a bionomial random variable. And randomness of the second part, inter-cell, is due to propagation channel (especially shadow fading), intermittence, and variant locations of the neighboring MS's. We need a suitable distribution for inter-cell interference and with respect to [2] and [10], and in case of voice only traffic gamma distribution appears to be a proper choice with the assumption of uniform spatial traffic distribution in the neighboring cells. Hence, in applying this distribution at any (i, j, k) traffic state, we require the mean and variance of the interfering effects of the neighboring cells' users at that state. But we have a large number of states corresponding to various traffic status of the neighboring cells and each state leads to a specific mean and variance, or equiavalently a specific inter-cell interference distribution. Hence, we are obliged to limit ourselves to a few number of these states in order to be able to track the related equations mathematically and this will lead to an approximate solution for our traffic analysis. One of the main advantages of our geographical structure reverts to its flexibility to include limited traffic states corresponding to neighboring cells. To simplify our analysis further, we focus on the first tier of neighboring cells' users as the dominant interfering users on the desired cell. Thus, for our traffic model we need only the traffic parameters of the desired cell (cell A) and first tier of interfering cells (like cell B).

In order to simplify the related traffic equations, the limiting scheme used for our traffic model is to estimate the number of dominant inter-cell interfering users, i.e., network-admitted users in the first tier of interfering cells, at each (i, j, k) traffic state by an estimation which takes into account k, the number of users in SHR_2 . For the sake of simplicity, we employ linear estimation that is justified with the assumption of uniform spatial traffic distribution at each neighboring cell. In this methodology, we are able to evaluate the mean and the variance, or equivalently distribution, of inter-cell interference for the desired cell at each traffic state distinctly. Due to lack of sufficient information corresponding to first tier of interfering cells, especially the traffic status of their neighbors (e.g., second tier with respect to cell A), we are obliged to employ average traffic parameters corresponding to these cells. Thus, we need to estimate the corresponding average traffic parameters at the onset that leads to an iterative approach in solving the related equations. In fact, after solving the related equations we are able to compute the respective average traffic parameters corresponding to the desired cell, which are then considered as new estimates for the respective average traffic parameters corresponding to the neighboring cells. Obviously, iterations should be continued until the corresponding average traffic parameters for the desired cell converge to the respective estimates, since in our scheme we assume that the estimates obtained for various average traffic parameters of the first tier of neighboring cells correspond to the same average traffic parameters of the desired cell. However, in the case of discrepency between some of the primary traffic parameters (such as new call arrival rate) at cell A and its neighbors, such assumption can be justified by suitable setting of corresponding thresholds at the neighboring cells. Also, to simplify further, we assume the same conditions for various traffic status and parameters for all the first tier of neighboring cells, however, this assumption can be removed by proper changes in the traffic equations.

With respect to above discussions, we can compute the mean and the variance of interfering effects of the neighboring cells as follow:

$$\begin{aligned} E(m) &= e(k)\,\nu f_1; \\ \mathrm{var}(m) &= e(k)\,\nu f_2; \\ f_1 &= 0.57, f_2 = 0.22, \end{aligned} \tag{12}$$

$$\begin{aligned} P_{\mathrm{int}}(m) &= \frac{1}{\Gamma(\rho)}\alpha^{\rho} m^{\rho-1}\exp(-\alpha m); \\ E(m) &= \frac{\rho}{\alpha}, \mathrm{var}(m) = \frac{\rho}{\alpha^2} \end{aligned} \tag{13}$$

where P_{int} is inter-cell interference distribution (gamma distribution), m is the normalized real-valued number of inter-cell interferers (it is equal to the ratio of inter-cell interference on the interference of an intra-cell user), ν is the voice activity factor, and $e(k)$ is the estimate of the number of inter-cell interferers in each neighboring cell and for uniform estimation $e(k)$ will equal to k multiplied by the ratio of the area of one cell to the area of SHR_2. Furthermore, f_1, f_2 are coefficient factors assigned to the mean and the variance of the interference due to active users in the neighboring cells. Their values are assumed constant in all traffic states, and are similar to those used in [2].

The blocking (inner-cell blocking) and dropping probabilities at each traffic state (i.e., conditional probabilities) with respect to current short-term interference level and using the above assumptions, will be computed as follows:

$$\begin{aligned} P_{B(D)}(i,j,k) &= \sum_{u=0}^{i+j} b(u;i+j,\nu)\int_{T_{Block(Drop)}-u}^{\infty} P_{\mathrm{int}}(m)dm; \\ b(u;i,\nu) &= \binom{i}{u}\nu^u(1-\nu)^{i-u} \end{aligned} \tag{14}$$

where the subscript $B(D)$ corresponds to blocking (dropping) and $T_{block(drop)}$ is the threshold corresponding to blocking (dropping) a new (handoff) call request. And $b(u;i,\nu)$ corresponds to the probability of u interfering (active) users with i connected users in the desired cell. The first term of the argument of Σ in (14), i.e., $b(u;i+j,\nu)$, indicates intra-cell interference and the second term, i.e., the integral term, represents the inter-cell interference at (i, j, k) traffic state. The blocking and dropping probabilities in each region should be computed according to a specific traffic management policy.

In order to obtain average blocking (dropping) probabilities and other traffic parameters we need to solve global balance equations (GBE) corresponding to the Markov chain in Fig. 2 to evaluate stationary probabilities, $\pi(i,j,k)$ (see Appendix B). Thus, we have some average traffic parameters as follow:

$$\overline{P_{B(D)}} = \sum_{i=0}^{\mathrm{Max}(i)}\sum_{j=0}^{\mathrm{Max}(j)}\sum_{k=0}^{\mathrm{Max}(k)} \pi(i,j,k)P_{B(D)}(i,j,k), \tag{15}$$

$$\text{Carried Traffic} = \sum_{i=0}^{\mathrm{Max}(i)}\sum_{j=0}^{\mathrm{Max}(j)}\sum_{k=0}^{\mathrm{Max}(k)} \pi(i,j,k)(i+j), \tag{16}$$

$$\overline{P_{loss}} = \sum_{i=0}^{\mathrm{Max}(i)}\sum_{j=0}^{\mathrm{Max}(j)}\sum_{k=0}^{\mathrm{Max}(k)} \pi(i,j,k)P_{loss}(i,j,k) \tag{17}$$

where

$$P_{loss}(i,j,k) = \frac{\sum_{u=0}^{i+j} b(u;i+j,\nu)u\int_{C_{\max}-u}^{\infty} P_{\rm int}(m)dm}{\sum_{u=0}^{i+j} b(u;i+j,\nu)u}. \quad (18)$$

$P_{loss}(i,j,k)$ defines the quality loss at (i, j, k) traffic state, i.e., it indicates the average fraction of time that the active MS's will confront degradation in their QoS due to large interference [2].

In the above equations $C_{\max}$ is the maximum allowable real-valued number of interfering users with respect to required value of SIR, and can be obtained by [2]:

$$C_{\max} = 1 + \frac{pg(1-\eta^{-1})}{\frac{E_b}{I_{0,req}}} \quad (19)$$

where pg is the processing gain, E_b is the bit energy, $I_{0,req}$ is the acceptable maximum total interference power density, and $\eta = I_{o,req}/N_o$ (N_0 is the thermal noise power density). We, usually, normalize the thresholds to $C_{\max}$. In the above equations for computational purposes we limit the number of users in each region, however, this limit should not be the limiting factor in soft capacity due to ICAC modeling (see Appendix B).

IV. Conclusion

In this paper we discussed two important features of the CDMA cellular network, i.e., soft capacity and soft-handoff, and their effect on the traffic analysis and modeling. We then discussed traffic analysis of the CDMA cellular network especially with respect to interference-limitedness attribute of its capacity. After describing the important issues of a traffic model for such a network we proposed a new and flexible reverse link traffic model. This traffic model is built upon ICAC method for soft capacity consideration and includes time-varying traffic status of the neighboring cells in computing inter-cell interference and handoff rate by using triple regions in its geographical structure. Also, this model is suitable for analysis and especially for comparison of traffic and handoff management algorithms in dynamic environments.

Appendix A

Computing average sojourn time in different regions is performed according to [13, appendix A]. Also, we compute new call origination rate and departure rate for different regions as follow:

$$\lambda_{n_u} = \lambda_{n_R}\frac{A_{R_u}}{A_R} \quad (A.1)$$

$$\mu_{R_i} = \mu_R 2^{-\log_{10}(A_{R_i}/A_R)}$$
$$\mu_{r_i} = \mu_R 2^{-\log_{10}(A_{r_i}/A_R)} \quad (A.2)$$

where A_{R_u} is the area of region u and A_{r_i} is the area of one subregion of region i. These equations have been written with the assumption of the same primary traffic parameters at cell A as well as its neighbors. However, this assumption can be removed in the case of heterogenous traffic intensities for the concerning cells.

Handoff rate at each (i, j, k) traffic state with the assumption of uniform spatial traffic distribution at neighboring cells will be as follows:

$$\lambda_{h_{43}} = k\left(\frac{A_{R_1}}{A_{r_3}}\frac{\mu_{R_1}}{6}\right) + k\mu_{r_3}P_{tr_{22}}. \quad (A.3)$$

We observe that we consider handoff arrival rate from neighboring cells as a traffic load dependent rate. This is one among the flexibilities of the proposed traffic model, since in most of the previous traffic models, a fixed average handoff rate is considered.

We assume the probability of moving in different directions according to border line length at each direction. Also, we consider these movements in each subregion. Therefore we will have:

$$\begin{aligned} P_{tr_{22}} &= \frac{2a}{2+a}, \\ P_{tr_{32}} &= P_{tr_{23}} = \frac{1}{2+a}, \\ P_{tr_{21}} &= \frac{1-a}{2+a}, \\ P_{tr_{34}} &= P_{tr_{22}} + P_{tr_{21}}. \end{aligned} \quad (A.4)$$

Appendix B

In this appendix we discuss the global balance equations (GBE) used for solving our Markov chain. For computational reasons we need to limit for the number of users in three regions as $\mathrm{Max}(i)$, $\mathrm{Max}(j)$, and $\mathrm{Max}(k)$. Because of accepting ICAC method for our traffic model, these numbers should not be the dominant factors in limiting the number of channels. In the analysis, we can determine these numbers such that the blocking and dropping probabilities exceed a threshold equal to 0.9 (by increasing this threshold we should not observe any noticeable change in the results). Obviously, these limits are determined adaptively, so, the number of states are reduced and the speed of numerical analysis is increased. The GBE in general is as in the following:

$$\begin{aligned} &\pi(i,j,k)(\lambda_{11}(i,j,k)+\lambda_{22}(i,j,k)+\lambda_{33}(i,j,k) \\ &\quad +\mu_{11}(i,j,k)+\mu_{22}(i,j,k)+\mu_{33}(i,j,k)+\lambda_{12}(i,j,k) \\ &\quad +\lambda_{21}(i,j,k)+\lambda_{23}(i,j,k)+\lambda_{32}(i,j,k)) \\ &= \pi(i-1,j,k)\lambda_{11}(i-1,j,k) \\ &\quad +\pi(i,j-1,k)\lambda_{22}(i,j-1,k) \\ &\quad +\pi(i,j,k-1)\lambda_{33}(i,j,k-1) \\ &\quad +\pi(i+1,j,k)\mu_{11}(i+1,j,k) \\ &\quad +\pi(i,j+1,k)\mu_{22}(i,j+1,k)+\pi(i,j,k+1)\mu_{33}(i,j,k+1) \\ &\quad +\pi(i+1,j-1,k)\lambda_{12}(i+1,j-1,k) \\ &\quad +\pi(i-1,j+1,k)\lambda_{21}(i-1,j+1,k) \\ &\quad +\pi(i,j+1,k-1)\lambda_{23}(i,j+1,k-1) \\ &\quad +\pi(i,j-1,k+1)\lambda_{32}(i,j-1,k+1); \\ &0 \le i \le \mathrm{Max}(i), 0 \le j \le \mathrm{Max}(j), 0 \le k \le \mathrm{Max}(k). \end{aligned} \quad (B.1)$$

In the general equation, some of the terms may be removed depending upon the specific (i, j, k) traffic state, if the corresponding indices exceed the adaptive computed maximum or become negative.

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