Efficiency Comparison of Channel Allocation Schemes for Digital Mobile Communication Networks

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***Abstract*—This paper provides network designers and operators with simple guidelines on traffic measurements and efficiency evaluation of various channel allocation schemes in digital mobile telecommunications networks. The paper evaluates the efficiency obtained by implementing the following channel allocation schemes: 1) fixed uniform channel allocation (FUCA); 2) fixed nonuniform channel allocation (FNCA); 3) dynamic channel allocation (DCA) where the number of frequency carriers is adaptive and dependent on the load; and 4) dynamic frequency/time channel allocation (DFTCA) (a new scheme which is the most efficient) where the number of channels is adaptive (based on the load), allowing two channels of the same frequency carrier to be used in two neighboring cells. The analysis is based on standard queuing models under the following assumptions: 1) Poisson call arrivals in each cell; 2) exponential call holding time; 3) exponential mobile travel time; and 4) exponential sojourn time of a mobile in a cell. Numerical results are presented to provide insight into accuracy of the models and efficiency gain by dynamic frequency time channel allocation under different traffic conditions (including conditions related to highway traffic).**

I. INTRODUCTION

WITHIN the past decade, the evolution of mobile telecommunication systems has gone through two generations of changes. These include changes from bulky high-powered equipment to handier low-powered handsets, from one tier architecture to hierarchical cell structure, and from analog to digital.

Currently, some of the common digital mobile systems (not to be confused with cordless phone systems) include the groupe spécial mobile (GSM) [1], [2] standard also known as global system for mobile communications, personal communication system (PCS1900) [3], [4], digital communication system (DCS1800) [1], digital advance mobile phone system (D-AMPS) [5]–[7], and Qualcomm code-division multiple-access (CDMA) system [8]–[10].

GSM is a pan-European standard that has been evolved into a globally accepted standard for digital cellular communications. GSM uses a combination of time-division multiple access (TDMA) and frequency-division multiple access (FDMA) with a pinch of frequency hopping. PCS1900 is the Ericsson mobile communication system that is a variation of GSM on the 1900-MHz band specifically adapted for the North American market. Supporting both integrated services digital network (ISDN) concepts and intelligent network (IN) functionality, PCS1900 also uses TDMA/FDMA combination. DCS1800 is another GSM-type system for the European market using the 1800-MHz band and TDMA/FDMA technology. D-AMPS is a standard used by cellular operators in the United States, Canada, and other countries. Again, it uses the combination of TDMA/FDMA for multiple access. The CDMA system is currently under study for the third-generation personal communication system (PCS).

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TABLE I

System	TDMA channels per carrier (c)	control/broadcast channels per cell (b)
GSM	8	1
PCS 1900	8	1
DCS 1800	8	1
D-AMPS	3	1

In this paper, we only consider digital mobile communication systems that use the TDMA/FDMA combination. These include all the above-mentioned systems except CDMA. In particular, we consider the case where each *cell* (as in cellular area) is allocated a certain number of frequency carriers, each frequency carrier is subdivided into a certain number of TDMA channels, and one or more of these TDMA channels is used for control and broadcasting by the base station. In Table I, we present the total number of TDMA channels per frequency carrier and the number of control/broadcasting channels per cell.

With the current observed growth of demand for digital mobile telephony, increasing the capacity of existing networks is a major priority of the large telecommunications companies. It is clear that increased capacity will allows an increased number of customers, hence bringing in steadily larger revenues. One way of increasing capacity is to install more base stations, which is based on the principle of continued use of current equipment, but in greater numbers. However, besides being not economical, this solution is also restricted by limitation such as minimum cell size, maximum packing density, and frequency reuse planning. An alternative approach would be to enhance the current equipment so that capacity growth is achieved through better efficiency rather than increased quantity. This is no doubt a more elegant solution that could reduce substantially the capital expenditure required.

Current standards developments of TDMA/FDMA digital cellular mobile networks support fixed channel allocation

(FCA) where the number of frequency carriers in each cell stays fixed and does not vary according to the traffic load. Although the allocation of frequency carriers can be changed, the rearrangement is only done on a medium-term basis, that is, it is done in a nonreal-time fashion. This means the allocation relies heavily on frequency planning and will not be able to adapt dynamically to the changing condition of the offered traffic.

In view of this "deficiency" of FCA, recent standards developments support the use of dynamic channel allocation (DCA) in which the number of frequency carriers in each cell may vary depending on the traffic load. DCA is applied in the digital enhanced cordless telecommunication system (DECT) and the Japanese personal handyphone system (PHS). DCA is also currently supported by GSM and will be supported by PCS and D-AMPS in the near future as the incorporation of DCA into their evolving standards is in an advanced stage. The evaluation of the benefits of DCA over FCA is therefore important to telecommunications providers who are considering upgrading their existing channel allocation equipment.

A further improvement to DCA can be achieved by also allowing the time slots (TDMA channels) of each frequency carrier to be adaptively allocated possibly to different cells. In such a scheme, the same frequency carrier may serve several neighboring cells using different time slots. We will refer to this scheme as dynamic frequency/time channel allocation (DFTCA) [11]–[13]. DFTCA is not currently supported by any standards development. The practicality of assigning different time slots from the same frequency carrier to adjoining cells and managing the process in real time is not trivial. Centralized (or possibly distributed) management architecture, which is unavailable today, is required. Additional transmitters/receivers will have to be added onto all base stations providing this service so that they are capable of transmitting and receiving in all available frequency carriers. It may also be necessary for the handsets to be fitted with more sophisticated output power controlling mechanism to reduce possible interference and/or giving up some capacity to serve as "time band" (equivalent to guard band for FDMA) between time slots. Note that under DFTCA cells cannot be too large because of the effect of propagation delay that distorts the relative time positioning of distance mobiles and hence, requires larger time band. On the other hand, as in DCA, cells cannot be too small because that will increase intercell interference. The investigation into the optimal cell size and other implementation issues and technical obstacles are beyond the scope of this paper. Instead, we focus here on teletraffic aspects aiming to evaluate the efficiency benefit of DFTCA. Such evaluation may provide support for justification of the significant additional cost of implementing DFTCA including the cost of upgrading all base stations with multiple transceivers.

In this paper, we consider the following four schemes: 1) fixed uniform channel allocation (FUCA) where all cells, regardless of the traffic loading, have the same number of frequency carriers at all times; 2) fixed nonuniform channel allocation (FNCA) where the number of frequency carriers in each cell is set to be the smallest number of frequency carriers such that overall blocking probability requirement is maintained; 3) DCA; and 4) DFTCA. We compare the efficiency of these four schemes under the assumptions of Poisson call arrivals, exponential call holding time, and mobile travel time as well as the assumption that the time the mobile stays in a cell is exponential. In particular, the analytical model is based on the independence assumption that the traffic behavior in each cell is independent of the traffic behavior in all other cells. The arrival and the departure rates in each cell are based on (average) flow equations as in [14] and [15].

In previous related papers, see for example [16], the aim was to develop an analytical approximation to evaluate performance measures such as blocking probability. Also, [16] did not allow for the GSM-type structure where channels are grouped into frequency carriers. The analytical method proposed here is aimed at efficiency evaluation. It provides network designers and operators with simple guidelines on traffic measurements and efficiency evaluation of the different channel allocation schemes in digital mobile telecommunications networks. Our approximate analytical models and guidelines are verified by simulation.

To increase capacity, the use of layered network architecture has been proposed and widely discussed in the literature (see [17]–[20] and [21] and references therein). In this paper, we focus on the widely used single-layered architecture. It must also be made clear that in this paper, we do not allow for multiple handover attempts as described in [1], in the event of a handover failure, the call is dropped without further attempts.

The remainder of the paper is organized as follows. Section II describes the model used and the various schemes under consideration. The methods used for evaluating the efficiency of the different schemes are described in Section III. In Sections IV and V, we provide a comprehensive set of traffic conditions to examine the accuracy of the analytical models. In particular, in Section IV, we consider a 49-cell wrap-around topology with symmetrical traffic conditions, while in Section V, we consider a "highway-type" traffic pattern for the same topology. The examinations show that the analytical models are accurate in most cases of symmetrical or light traffic cells and conservative for the heavy traffic cells.

II. The Models

Consider a cellular mobile network with N cells denoted: $1, 2, 3, \cdots, N$. We assume that the time a mobile stays in cell i is exponentially distributed with mean m_i, $i = 1, 2, 3, \cdots, N$, the holding time is exponentially distributed with parameter $1/\mu$, and the generation of calls in cell i follows a Poisson process with parameter λ_i. Let P_{ij} be the probability that a mobile will move to cell j in its next hop given that it completed its sojourn in cell i. Henceforth, the matrix $[P_{ij}]$ will be called the *handover probability matrix*. The exponential and Poisson assumptions are for tractability. Nevertheless, the exponential holding time and the Poisson generation of calls has been used for many years in telephony.

The traffic in each cell is served by one or more frequency carriers. Let c be the total number of channels per frequency carrier, and let b be the number of control/broadcasting channels per cell. For example, as shown in Table I, for GSM, $c = 8$ and $b = 1$ (i.e., each frequency carrier has eight channels, that is, it can serve eight calls simultaneously and one channel per cell is always reserved for broadcasting by the base station). Therefore, if in a given cell i, the number of frequency carriers is K_i, the number of traffic channels available in that cell, denoted k_i is given by

$$k_i = c \times K_i - b. \tag{1}$$

Four schemes are considered next.

A. Fixed Uniform Channel Allocation

Under FUCA, the number of frequency carriers is fixed during the operation. As discussed, all cells, regardless of the traffic loading, have the same number of frequency carriers. In the model, this number is set to be the smallest number of frequency carriers such that the overall blocking probability requirement is maintained for all cells.

B. Fixed Nonuniform Channel Allocation

This is another scheme where the number of frequency carriers stays fixed during the operation. However, unlike FUCA, under this scheme, the number of frequency carriers in each cell is set to be the smallest number of frequency carriers such that overall blocking probability requirement is maintained. In this case, cells with higher traffic loading may have more frequency carriers than those with less traffic.

C. Dynamic Channel Allocation

Under this scheme, unlike the previous two schemes, the number of frequency carriers in each cell is adaptively changed to accommodate traffic fluctuations. During heavy traffic periods in a given cell, more frequency carriers will be available for that cell, while it may be reduced during light traffic periods to be used by other cells. At any point in time, the number of frequency carriers in each cell is set to be the smallest such that all calls can be served. It is assumed that intracell handovers are allowed for efficiency (i.e., calls within a cell are repacked [22], [23]). For example, if there are seven calls in progress in a given cell supported by two frequency carriers, all seven calls will be repacked into a single-frequency carrier and the second carrier will be released for possible use by other cells. For tractability, we assume that new frequency carriers are always available. That is, for each cell we assume an $M/M/\infty$ queuing system; and the number of frequency carriers assigned to cell i is

$$K_i = \left\lceil \frac{n+b}{c} \right\rceil \quad \text{for } n = 0, 1, 2, \cdots \tag{2}$$

whenever cell i is in state n (the number of active calls in that cell is n). The notation $\lceil x \rceil$ is used for the smallest integer greater than or equal to x.

D. Dynamic Frequency Time Channel Allocation

Under this scheme, in addition to the frequency carriers being adaptively allocated in accordance with the traffic load (as in DCA), the time slots of each carrier can also be adaptively allocated. In other words, two calls in progress in two neighboring cells may use the same frequency but at different time slots. The concept of channel is now based on time/frequency division. As in DCA, we assume that new channels are always available. That is, for each cell we assume an $M/M/\infty$ queuing system.

III. Analysis

Let $\hat{P}_{ij}$ be the probability that a mobile that enters cell i will hop to cell j in its next hop. By definition we have

$$\hat{P}_{ij} = \frac{\frac{1}{m_i}}{\frac{1}{m_i} + \mu} P_{ij}. \tag{3}$$

Let $\hat{\mu}_i$ be the effective departure rate of cell i. That is, $\hat{\mu}_i$ represents the total departure rate that includes call completion rate in cell i plus call handover rate to neighboring cells. By definition we have

$$\hat{\mu}_i = \mu + \frac{1}{m_i}. \tag{4}$$

Let $\hat{\lambda}_i$ be the effective arrival rate into cell i. That is, $\hat{\lambda}_i$ represents the total arrival rate which includes call generation rate in cell i plus call handover rate from neighboring cells into cell i. By definition we have

$$\hat{\lambda}_i = \lambda_i + \sum_{j \neq i} \hat{\lambda}_j \hat{P}_{ji}, \qquad \text{for } i = 1, 2, 3, \cdots, N. \tag{5}$$

The concept of efficiency is defined by the ratio between the average number of channels utilized and the average number of channels allocated. We now describe how we obtain the efficiency for each of the schemes.

A. Fixed Nonuniform Channel Allocation

For cell i we assume an $M/M/k/k$ queuing system with parameters $\hat{\lambda}_i$ and $\hat{\mu}_i$. The value of the number of frequency carriers K [which is directly related to the number of allocated channels k by (1)] is selected as the smallest possible number such that the overall blocking probability requirement, denoted P_B, is maintained for all cells. In particular, we calculate for every cell i the minimum number of carriers, denoted K_i, required to satisfy overall blocking probability P_B. Then we set $K = \max\{K_1, K_2, K_3, \cdots, K_N\}$. The number of channels available to each cell is the same for all cells and is given by

$$k = c \times K - b. \tag{6}$$

The average number of utilized channels in cell i, denoted $E[n(i)]$, is obtained by a standard method of solving the steady-state equations of the Erlang system $M/M/k/k$ obtaining the steady-state probabilities $p_x(i)$, $x = 0, 1, 2, \cdots, k$ of having x busy channels in cell i. Then we obtain

$$E[n(i)] = \sum_{x=0}^{k} x p_x. \tag{7}$$

The efficiency for cell i, denoted ε_i, is calculated by

$$\varepsilon_i = \frac{E[n(i)]}{b+k} \tag{8}$$

and the overall efficiency, denoted ε, is calculated by

$$\varepsilon = \frac{\sum_{i=1}^{N} E[n(i)]}{N(b+k)}. \tag{9}$$

B. Fixed Nonuniform Channel Allocation

In the case of FNCA, the number of channels allocated is calculated separately for each cell. Again, for cell i we assume an $M/M/k/k$ queuing system with parameters $\hat{\lambda}_i$ and $\hat{\mu}_i$. The set $\{K_1, K_2, K_3, \cdots, K_N\}$ is calculated as for FUCA and the set $\{k_1, k_2, k_3, \cdots, k_N\}$ is then calculated by (1). The average number of busy channels in cell i, $E[n(i)]$, is obtained as for FUCA by (7). The efficiency for cell i is calculated by

$$\varepsilon_i = \frac{E\lfloor n(i) \rfloor}{b + k_i} \tag{10}$$

and the overall efficiency is calculated by

$$\varepsilon = \frac{\sum_{i=1}^{N} E[n(i)]}{\sum_{i=1}^{N}(b + k_i)}. \tag{11}$$

C. Dynamic Channel Allocation

Also, in the case of DCA the number of channels utilized and allocated is calculated separately for each cell. However, here we use the $M/M/\infty$ queuing model with parameters $\hat{\lambda}_i$ and $\hat{\mu}_i$ for cell i. The average number of busy channels for cell i is therefore given by

$$E[n(i)] = \frac{\hat{\lambda}_i}{\hat{\mu}_i}. \tag{12}$$

The probabilities $p_n(i)$, $n = 0, 1, 2, \cdots$ of having n number of busy channels in cell i are obtained by standard solution of the $M/M/\infty$ queuing model steady-state equations.

Let a_i be a random variable representing the number of channels allocated to cell i. Allowing always for b channels for control/broadcasting, by (1) and (2), the average number of channels allocated to cell i given n channels are active, denoted $E[a_i \mid n]$, is given by

$$E[a_i \mid n] = c \left\lceil \frac{n+b}{c} \right\rceil, \quad n = 0, 1, 2, \cdots \tag{13}$$

so the mean $E[a_i]$ is given by

$$E[a_i] = \sum_{n=0}^{\infty} p_n(i) E[a_i \mid n]. \tag{14}$$

The efficiency for cell i is calculated by

$$\varepsilon_i = \frac{E[n(i)]}{E[a_i]} \tag{15}$$

and the overall efficiency is calculated by

$$\varepsilon = \frac{\sum_{i=1}^{N} E[n(i)]}{\sum_{i=1}^{N} E[a_i]}. \tag{16}$$

D. Dynamic Frequency Time Channel Allocation

As in the case of DCA the number of channels utilized and allocated are calculated separately for each cell. Again, here we use the $M/M/\infty$ queuing model with parameters $\hat{\lambda}_i$ and $\hat{\mu}_i$ for cell i. The average number of busy channels for cell i is therefore given by (12).

Unlike the case of DCA, under DFTCA the number of channel allocated at any point in time in cell i is always equal to the number of active channels in that cell plus the number of channels used for control and broadcasting. Hence, the average number of channels allocated to cell i is given by

$$E[a_i] = E[n(i)] + b. \tag{17}$$

Again, the efficiency of cell i is calculated by (15) and the overall efficiency is calculated by (16).

Certain simple observations can be made to determine the difference in efficiency between that of DFTCA, the most efficient scheme, and the other three schemes. Clearly, when the traffic is very light in a given cell, the difference in efficiency is very high. This is because the other schemes are based on assigning the minimum number of carrier frequencies to the cells while DFTCA is based on assigning the minimum number of channels. For example, if the total number of busy channels in every cell is less then $c/2$, the benefit of DFTCA over the other FCA schemes will be of over 100% in efficiency. On the other hand, if the traffic is heavy, the benefit gain by DFTCA may not be that significant.

For a fixed total traffic loading, large variation in load for different cells will also result in higher efficiency gain by DFTCA by comparison to a case where the traffic is evenly distributed over all cells. This is because of the significant benefit in efficiency gained by DFTCA in lightly loaded cells.

IV. Symmetrical Traffic

In this section, we consider a 49-cell network as shown in Fig. 1(a). The cells are organized in seven clusters, each of seven cells. The seven clusters are denoted $C1, C2, \cdots, C7$ as shown in Fig. 1(b). The edges of the network are wrapped around such that the "edge effect" is minimized.

We assumed that each carrier frequency can support eight channels $(c = 8)$ and each cell uses one channel for control and broadcasting $(b = 1)$. For the FCA schemes, the overall blocking probability requirement is set to 1%.

In Sections IV-A and B, we consider traffic scenarios where the traffic is symmetrical. The meaning of symmetric is taken in the sense that every cluster is subject to the same traffic pattern, although individual cells in a particular cluster may differ in their traffic parameters. For example, in Fig. 1(a), all cells denoted by number 1 have the exact same traffic parameters. This is also true for all cells denoted by any particular number. On the other hand, cells with different numbers may have different traffic parameters.

Due to this symmetrical property, it is enough to focus the performance evaluation on only one of the seven clusters although the simulation must be carried out for all 49 cells.

Note that for Sections IV-A and B, in the simulation models a reuse distance of one is selected. That is, for FUCA, FNCA

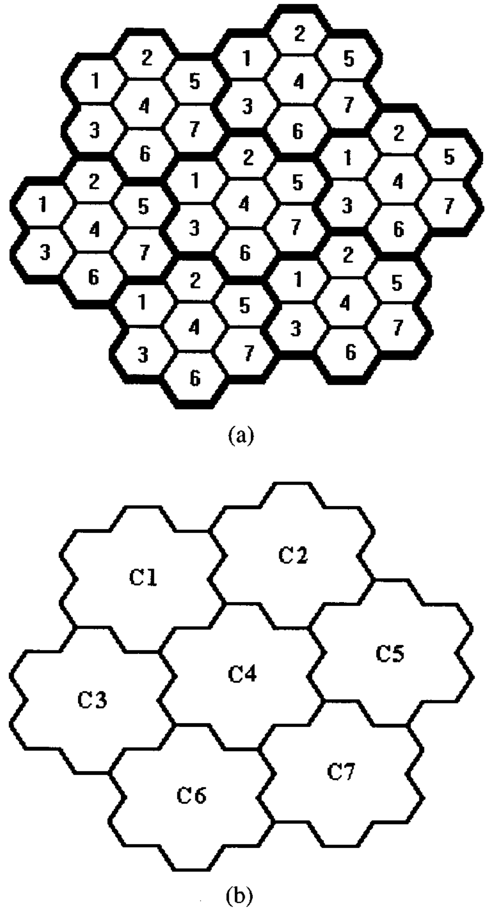

Fig. 1. The 49-cell cellular network used in simulation.

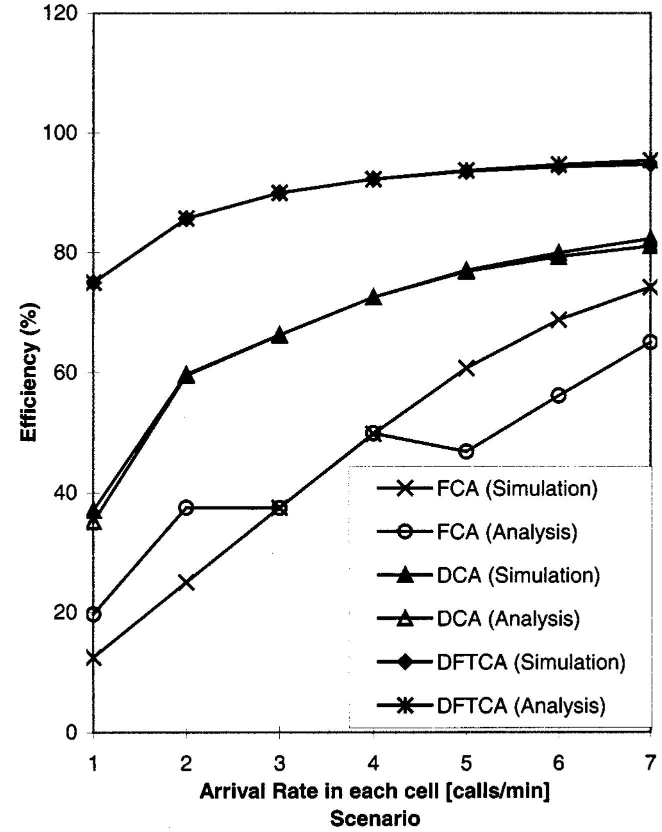

Fig. 2. Effect of arrival rate on efficiency.

and DCA, no two neighboring cells may utilize the same frequency carrier simultaneously. In the case of DFTCA, the restriction requires that no two neighboring cells may utilize the same channel simultaneously. This restriction is for the purpose of combating intercell interference.

A. Effects of Arrival Rate

This section considers the 15 traffic scenarios to study the effect of the arrival rate as well as the arrival distribution and handover distribution have on the various channel allocation schemes and the accuracy of the models.

For Scenarios 1–7, we have used here the handover matrix, P, defined by $P_{ij} = 1/6$, for all i and j. The probability of a mobile will move to any of the neighboring cells in its next hop given that it has completed its sojourn in cell i is exactly equal. The handover rate is set at $1/2$ calls/min $(m_i = 2)$ and the call holding time at 3 min $(\mu = 1/3)$ for all i. The call arrival rate is the same in all cells, and the call arrival rate for each cell i, $\sum \lambda_i$ is increased by 7 calls/min for each scenario. That is, $\lambda_i = 1$ for all i for the first scenario; $\lambda_i = 2$ for all i for the second scenario and so on.

The results of Scenarios 1–7 are presented Fig. 2. This demonstrates that as the total arrival rate increases, the efficiency of all schemes increases, but the efficiency gained by DFTCA over the other schemes decreases. Such is the benefit of DCA over the two FCA schemes. For these seven scenarios, because the load is evenly distributed, there is no efficiency gain by FNCA over FUCA. The same is true for both the analytical results as well as the simulation results. Since the curves are indistinguishable, we use one curve, denoted FCA to represent both FUCA and FNCA. As expected, we find agreement between the analytical and the simulation results. The very small differences between the analytical and the simulation results observed in the cases of DCA and DFTCA are only related to loss of traffic due to overall blocking in the simulation. (The reader in reminded that the analytical model does not assume any blocking for the cases of DCA and DFTCA.) The increase of efficiency for the two FCA schemes is not as “smooth” as the other two curves (for and analytical result of DCA and DFTCA) because for the FCA schemes, the increments in capacity are equal to an entire frequency carrier while the overall blocking probability requirement is fixed (set to 1%). Hence, it is impossible to achieve the exact same overall blocking probability for all scenarios. For example, in the case of the two FCA schemes, the overall blocking probability under Scenario 3 (where $\lambda_i = 3$ calls/min for all i) is 0.004%, while under Scenario 4 (where $\lambda_i = 4$ calls/min for all i) it is 0.16%. The differences between the analytical and the simulation results in the case of FCA can be explained by the “smoothing” effect due to handovers, which will be discuss in Section IV-B. Notice that the analytical model does not consider the handover effect while the simulation model does.

Scenarios 8–11 are based on the same handover probability matrix described earlier (used for Scenarios 1–7). The handover rate and holding time are also as before. In these scenarios,

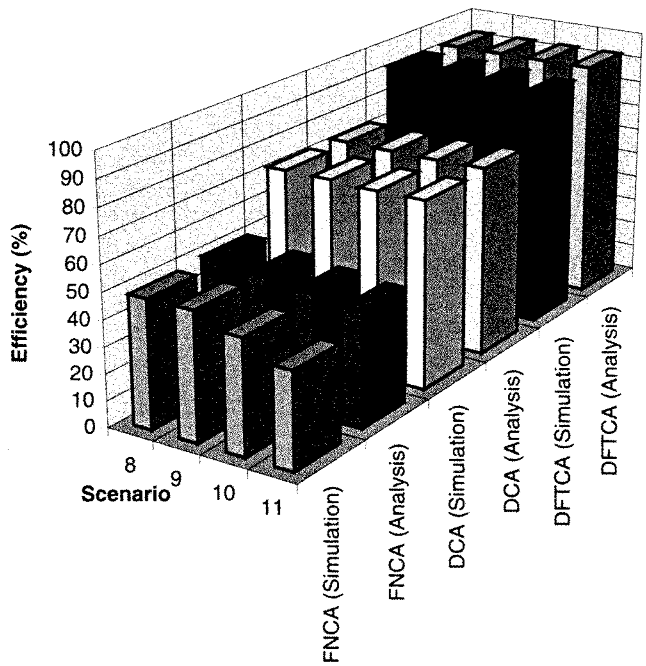

Fig. 3. Effect of arrival distribution on efficiency.

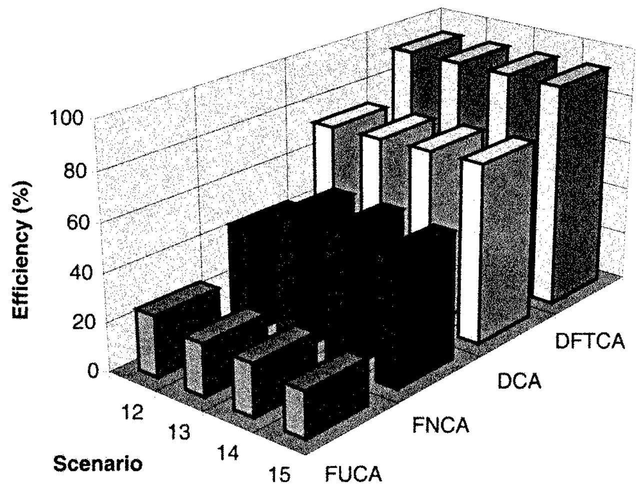

Fig. 4. Effect of handover distribution on efficiency.

the total arrival rate per minute remained fixed (i.e., $\sum \lambda_i =$ constant). The arrival rate for the cells gradually changes from a case (Scenario 8) where it is evenly distributed to a case (Scenario 11) where cell 4 has the majority of the calls while all other cells have very light load.

The analytical and the simulation results for Scenarios 8–11 are presented in Fig. 3. Again, we observe good agreement between the simulation and the analytical results. A certain discrepancy between these results is observed in the scenarios with more concentrated traffic where the overall blocking probability is higher. We also observe in Fig. 3 the benefit in efficiency of using DFTCA and DCA over the FNCA.

Scenarios 12–15 are similar to those of Scenarios 8–11 except that the probability matrix is now set such that $P_{i4} = 9/10$ and $P_{4i} = 1/6$, where $i \neq 4$, while $P_{ij} = 1/50$, where $i \neq 4$ and j is a neighboring cell to i and $j \neq 4$. In other words, for every cluster, mobiles are more likely to move to cell 4 which is the cell in the center of the cluster. Analytical results for these scenarios are presented in Fig. 4.

The results of Scenarios 8–11 and 12–15 are presented in Figs. 3 and 4, respectively. They demonstrate that for a fixed total traffic loading, as the distribution of the load becomes more uneven, the efficiency of the two FCA schemes decreases. The efficiency of DCA increases slightly while the efficiency of DFTCA remained unchanged over the two sequences of scenarios. This is expected because, as mentioned earlier, DFTCA scheme allocates capacity in terms of channels. If the total load is fixed, changing the distribution will not affect the performance. This is an important characteristic because if the allocation scheme is independent of the traffic distribution, its performance will not degenerate when the traffic distribution changes. As seen in Figs. 3 and 4, the efficiency gained by DFTCA and DCA over the FCA schemes as well as the benefit of FNCA over FUCA increases as the traffic distribution becomes more uneven. This is consistent with the above-mentioned intuitive observations. Again, the efficiency of FNCA for Scenario 12 is low because of the increments in capacity are equal to an entire frequency carrier while the overall blocking probability requirement is fixed (set to 1%), as discussed above.

B. Effects of Handover Rate

This section studies the effect of handover rate on the accuracy of the approximate analytical model. Notice that the analytical model is based on the independence assumption that the traffic behavior in each cell is independent of the traffic behavior in all other cells. It is therefore expected that if the handover rate is zero, the independence assumption holds and the analytical model will be accurate for the case of FUCA and FNCA. (Recall that for DCA and DFTCA we have an additional assumption that the number of available frequency carriers is unlimited.) It is therefore of interest to study the effect of handover rate on the accuracy of the approximate analytical model.

To this end, a simulation was performed using the probability matrix of Section IV-A, a holding time of 3 min $(\mu = 1/3)$ and an arrival rate of 4.82 calls/min $(\lambda_i = 4.82)$ for all cells. (This was selected to maximize the efficiency of the FUCA scheme when the handover rate is zero.)

Fig. 5 shows, by simulation, the effect of handover rate $1/m_i$ on efficiency for the different schemes. We observed that, for a fixed overall traffic, as the handover rate increases, the efficiency of FUCA decreases slightly, the efficiency of DCA decreases even less while the efficiency of DFTCA is unchanged. The loss of efficiency in DCA and FUCA for higher handover rate is due to the following reason. The increase of handover rate causes an increase in the burstiness to the overall arrival rate (call generations and call handover into a cell) and the overall departure rate (call terminations and call handover out of a cell) to a cell. This increase of burstiness, in turn, causes a higher overall blocking probability (new calls blocking and handover blocking) that leads to lower efficiency. With the DCA ability, the impact of higher burstiness on DFTCA is insignificant since a mobile moving into a neighboring cell will most likely not be lost due to insufficient capacity. This is because, at worst case, this migrating call may still be served using the existing channel

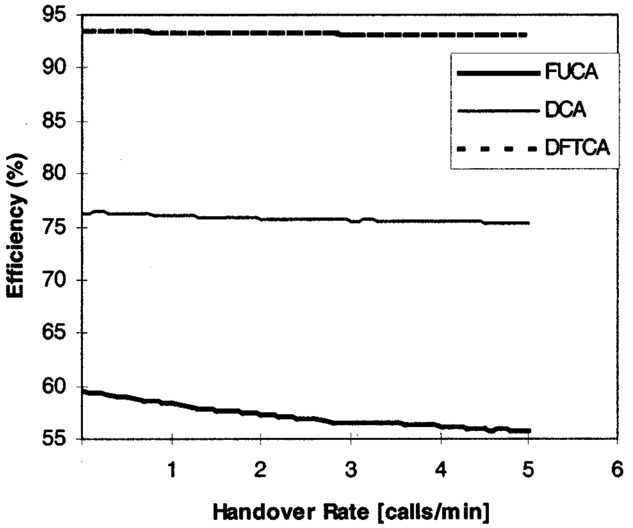

Fig. 5. Effect of handover rate on efficiency.

from the originating cell. This is a desirable characteristic of any channel allocation scheme.

V. Arterial Highway Traffic

In Section IV, the traffic patterns used were all symmetrical, and the behavior of both the analytical models and the simulations are close, therefore it is expected that the analytical results agree with the simulation results. However, in a realistic network, in many cases, the mobile traffic has a very definite bias. The majority of the traffic will be saturated along the highways, and for this reason, the mobile network providers locate their base stations as well as allocate channel capacity accordingly. Although in Section IV, Scenarios 11–15 address this realism partially (having one cell with much heavier traffic than the others), it would be interesting to evaluate the performance of the various channel allocation schemes as well as the accuracy of the models under such realistic traffic conditions where all cells along a certain path are having much heavier traffic.

In this section, we again consider a wrap-around 49-cell topology. However, here we consider a traffic pattern typical of a arterial highway system. This includes significant number of call generations and handover along the highways while the traffic reduces as the distance from the highways increases. In Fig. 6, the darker colored cells correspond to higher traffic loading (higher generation and handover rates). In Table II, these rates are presented for each of the four colored cell groups. Certain cells in the network presented in Fig. 6 are designated by a number. These are the cells in which performance evaluation will be performed. They include representatives from all of the four color groups mentioned above.

The cells in Fig. 6 can be classified into three classes based on their handover probabilities. (Note that this classification is different from the color shown in Fig. 6. The color in Fig. 6 as well as Table II are based on traffic loading.) Class 1 is those cells without any highway (cell 3, 47, 5, and 48). Class 2 is those cells with only a single bidirectional highway (cell 21 and 31). Class 3 is those cells with two bidirectional highway (cell 23 and 25 only). These classes have handover probabilities presented in

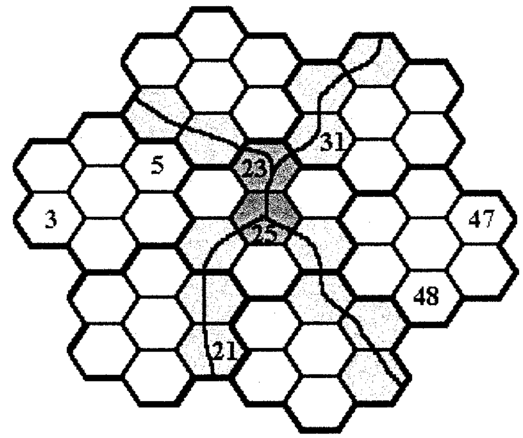

Fig. 6. "Highway-type" traffic pattern of a 49-cell network.

TABLE II
Simulation Parameters

Cell Colour				
Arrival Rate, λ_i [calls/min]	3	7	11	19.5
Handover Rate, μ_i [calls/min]	1	2.33	7.33	13
ID of sample cells	3, 47	5, 48	21, 31	23, 25

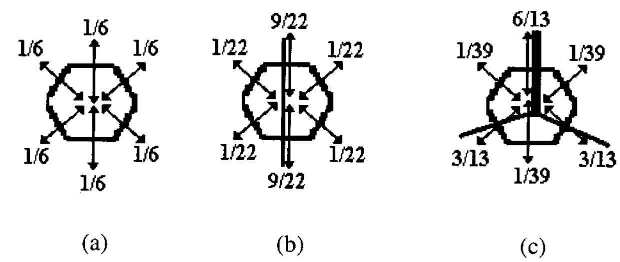

Fig. 7. Handover probabilities for the three classes of cells in Fig. 6.

Fig. 7 where Fig. 7(a)–(c) represents the handover probabilities of Classes 1–3, respectively. In Class 1 [Fig. 7(a)], the probability that a mobile will move to any neighboring cells in its next hop given that it has completed its sojourn in cell i is exactly equal ($P_{ij} = 1/6$ for all neighboring cell j where $j \neq i$). In Class 2 [Fig. 7(b)], the probability that a mobile in cell i will move along the highway to the next neighboring cell is 9/22 ($P_{ij} = 9/22$ for all neighboring cell j with a highway) while the probability that a mobile in cell i will move to a neighboring without a highway is 1/22 ($P_{ij} = 1/22$ for all neighboring cell j without a highway). In Class 3 [Fig. 7(c)], the probability that a mobile in cell i will move along the "twin" highway is 6/13 ($P_{ij} = 6/13$ for all neighboring cell j with a "twin" highway) while the probability that a mobile will move along the single highway is 3/13 ($P_{ij} = 3/13$ for all neighboring cell j with a single highway). The probability that a mobile will move to a neighboring that is without a highway is 1/39 ($P_{ij} = 1/39$ for all neighboring cell j without a highway).

In order to maintain the quality of service specified in Section IV, that is, in order for the overall blocking probability to be under 1%, we obtained by simulation that, each of the 49

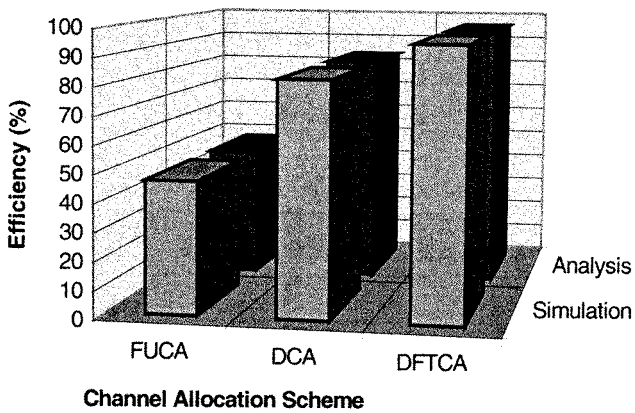

Fig. 8. Overall efficiency of the 49-cell network (Fig. 6).

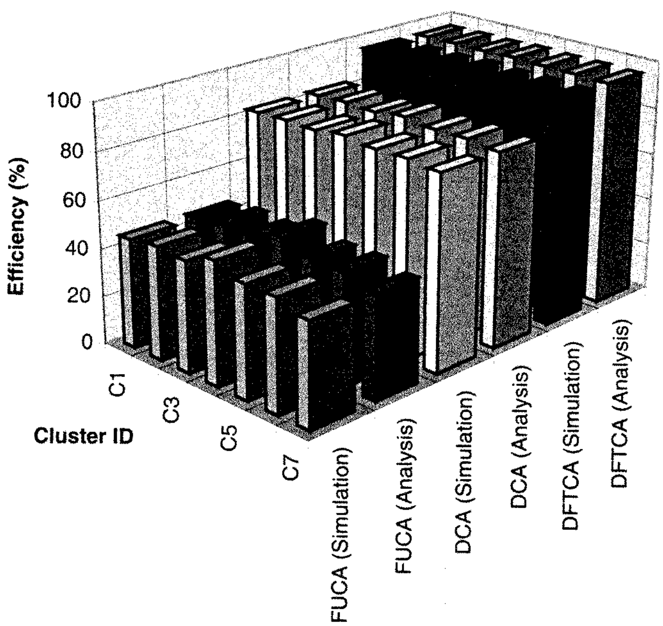

Fig. 9. Overall efficiency of the clusters for the 49-cell network (Fig. 6).

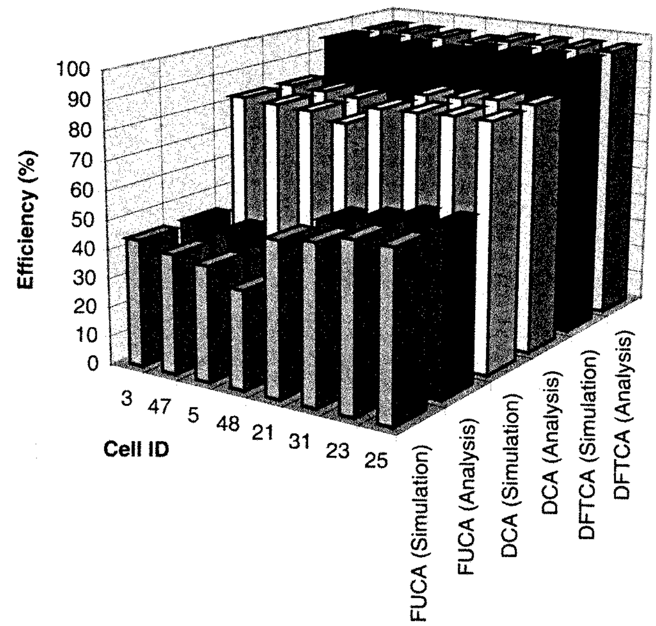

Fig. 10. Efficiency of the selected cells (Fig. 6) for the various schemes.

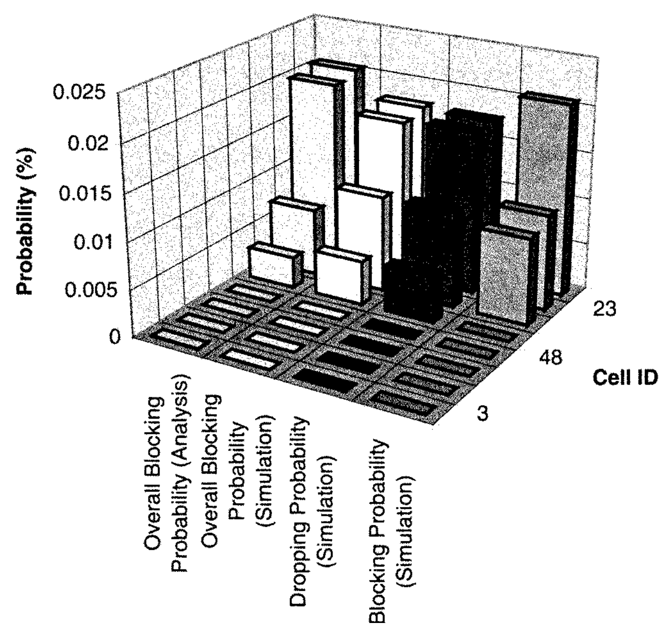

Fig. 11. Blocking, dropping, and overall blocking probabilities of the selected cells for FUCA.

cells should be allocated six frequency carriers under FUCA, five frequency carriers under DCA, and four frequency carriers under DFTCA. Again, for the simulation, a reuse distance of one is selected.

In Figs. 8–10, we compare the analytical and the simulation results. Fig. 8 shows the overall efficiency for the 49-cell network for FUCA, DCA, and DFTCA. The efficiency of the various schemes obtained by simulation is very close to those predicted by the analytical models.

Fig. 9 shows the overall efficiency of each of the clusters of seven cells in the 49-cell network. The cluster ID's are those shown in Fig. 1(b). Again, we see good agreement between the analytical results and the simulation results.

Now we present comparisons for the selected cells shown in Fig. 6. In Fig. 10, the efficiency comparisons of the analytical results and the simulation results for FUCA, DCA, and DFTCA are presented. Again, we see agreement between the analytical results and the simulation results.

Alongside the comparisons of the efficiency of the various channel allocation schemes, of particular importance, in the design of digital mobile telecommunication networks, is the *blocking probability* and the *dropping probability*. *Blocking probability* is the probability of a new call being blocked while *dropping probability* is the conditional probability that a call handovered from a neighboring cell is dropped. The reader is reminded that, in the analytical models, for FUCA and FNCA, these two probabilities are indistinguishable. In the analytical models, for FUCA and FNCA, the *overall blocking probability* (*analysis*) is the probability that all the available capacity has be used. In order to compare the analytical results and the simulation results, a weighted average of the *blocking probability* and the *dropping probability*, obtained in the simulation, is calculated by weighting the corresponding probabilities with the proportion of new calls and handover calls to obtain the *overall blocking probability* (*simulation*). The reader is also reminded that, under DCA and DFTCA, the analytical models assumes infinite capacity. As such, the *overall blocking probability* for DCA and DFTCA will always be zero. Notice also that our definition here of overall blocking probability is somewhat different from that in [12] and [13].

In Fig. 11, we present the a comparisons of the blocking probability obtained by simulation, the dropping probability obtained by simulation, the weighted average of the above two probabilities, and the overall blocking probability obtained by analysis.

We observed that the analytical models again provide a reasonable prediction of the overall blocking probability. The blocking and dropping probabilities from the simulation for DCA as well as DFTCA are very close to zero which is consistent with the dimensioning obtained by analytical models which assumes zero overall blocking probability for both cases.

VI. Conclusion

We have considered simple traffic models for efficiency evaluation of different channel allocation schemes based on the assumptions of Poisson call arrival and exponential call holding time and mobile travel time.

We have demonstrated by simulation that such simple models can be accurately used for dimensioning of TDMA/FDMA digital cellular mobile networks. Our simulation testing of the models consists of a range of scenarios including a practical case based on arterial highway traffic conditions.

Given the following traffic parameters: call arrival rate per cell, call holding time, mean mobile sojourn time in a cell, and the handover probability matrix, the network designer or operator could use the models presented here and their analysis to evaluate the efficiency of the different channel allocation schemes in digital mobile telecommunications networks.

We have evaluated the efficiency obtained by implementing the following channel allocation schemes: 1) FUCA; 2) FNCA; 3) DCA; and 4) DFTCA.

Numerical results obtained by the analytical model, which are verified by simulation, provide insight into efficiency gain under different traffic conditions. As the total arrival rate increases, the efficiency of all schemes increases, but the efficiency gained by DFTCA and DCA over the two FCA schemes decreases. For a fixed total traffic loading, as the distribution of the load becomes more uneven, the efficiency of the two FCA schemes decreases. The efficiency of DCA increases slightly while the efficiency of DFTCA remained unchanged over the two sequences of scenarios. Also, the efficiency gained by DFTCA and DCA over the FCA schemes as well as the benefit of FNCA over FUCA increases as the traffic distribution becomes more uneven.

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References

[1] M. Mouly and M. Pautet, *The GSM System for Mobile Communications*, France: Mouly and Pautet, 1992.

[2] *European Telecommunications Standards Institute (ETSI) Standards GSM Specifications Series 01–12*, 1992.

[3] R. Baines, "PCS1900: GSM as a candidate for US PCS applications," in *Proc. 3rd Annual Wireless Symp.*, Feb. 1995, pp. 101–112.

[4] *PCS 1900 The New Personal Communications System for North America*, Ericsson, TX, Dec. 1994.

[5] *800 MHz TDMA Cellular-Radio Interface-Mobile Station-Base Station Compatibility-Digital Control Channel*, Telecommunications Industry Association/Electronic Industries Association Interim Standard, TIA/EIA/IS-136.1, Dec. 1994.

[6] *800 MHz TDMA Cellular-Radio Interface-Minimum Performance Standards for Mobile Stations*, Telecommunications Industry Association/Electronic Industries Association Interim Standard IS-137, Dec. 1994.

[7] *800 MHz TDMA Cellular-Radio Interface-Minimum Performance Standards for Base Stations*, Telecommunications Industry Association/Electronic Industries Association Interim Standard IS-138, Dec. 1994.

[8] A. Baier, "Design study for a CDMA-based-generation mobile radio system," *IEEE J. Select. Areas Commun.*, vol. 12, May 1994.

[9] H. Chung, "The combining ATM with CDMA technology for PCS," in *Proc. 7th World Telecommunication Forum*, Geneva, Switzerland, 1995, pp. 193–197.

[10] *Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System*, Telecommunications Industry Association/Electronic Industries Association Interim Standard, TIA/EIA/IS-95, Dec. 1994.

[11] M. Zukerman and P. L. Hiew, "A simple model for efficiency evaluation of various channel assignment schemes in digital cellular mobile communication systems," in *Proc. Australian Telecommunication Networks and Applications Conf., ATNAC'96*, vol. 1, Melbourne, Australia, Dec. 3–6, 1996, pp. 333–338.

[12] ——, "Efficiency and quality of service comparison amongst several channel allocation schemes for digital cellular mobile communication systems," in *Proc. IEEE Global Communication Conf., GLOBECOM'97*, Phoenix, AZ, Nov. 3–8, 1997.

[13] ——, "Teletraffic issues related to channel allocation in digital mobile cellular networks," in *Proc. IEEE INFOCOM'98*, San Francisco, CA, 1998.

[14] E. J. Wilmes and K. T. Erickson, "Two methods of neural network controlled dynamic channel allocation for mobile radio systems," in *Proc. 46th Vehicular Technology Conf., VTC'96*, vol. 2, Apr. 1996, pp. 746–750.

[15] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," *IEEE Personal Commun. Mag.*, pp. 10–31, June 1996.

[16] D. L. Pallant and P. G. Taylor, "Approximation of performance measures in cellular networks with dynamic channel allocation,", Univ. Adelaide Teletraffic Research Center Rep., 1992.

[17] W. Jolley and R. Warfield, "Modeling and analysis of layered cellular mobile networks," in *Proc. 13th Int. Teletraffic Congress*, Copenhagen, Denmark, June 1991, pp. 161–166.

[18] M. Frullone, P. Grazioso, and A. M. Serra, "Performance evaluation of a personal communication system in a urban environment," in *Proc. 42nd IEEE Vehicular Technology Conf., VTC'92*, Denver, CO, May 1992, pp. 498–501.

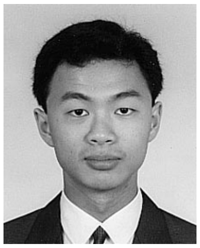
[19] L. Hu and S. S. Rappaport, "Personal communications systems using multiple hierarchical cellular overlays," in *IEEE Proc. Int. Conf. Universal Personal Communications, ICUPC 94*, San Diego, CA, Sept. 1994, pp. 397–401.

[20] S. S. Rappaport, "Blocking, handoff and traffic performance for cellular communications with mixed platforms," *Proc. Inst. Elect. Eng.*, vol. 140, pp. 389–401, Oct. 1993.

[21] P. Fitzpatrick and C. S. Lee, "Performance of layered cellular networks with overflow and nonuniform teletraffic demand," in *Proc. Int. Conf. Telecommunications, ICT 97*, vol. 1, Apr. 1997, pp. 57–62.

[22] M. Ivanovich, M. Zukerman, P. Fitzpatrick, and M. Gitlits, "Channel allocation methods for half and full rate connections in GSM," in *Proc. IEEE ICC'96*, Arlington, TX, June 1996.

[23] ——, "Performance analysis of circuit allocation schemes for half and full rate connections in GSM," in *Proc. 46th Vehicular Technology Conf., VTC'96*, Atlanta, GA, Apr.–May 1996.



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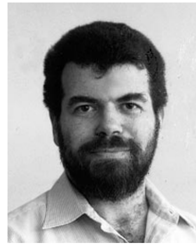

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