Abstract

In this article, we present a general cell-design methodology for the optimal design of a multitier wireless cellular network. Multitier networks are useful when there are a multitude of traffic types with drastically different parameters and/or different requirements, such as different mobility parameters or quality-of-service requirements. In such situations, it may be cost-effective to build a multitude of cellular infrastructures, each serving a particular traffic type. The network resources (e.g., the radio channels) are then partitioned among the multitude of tiers. In general terms, we are interested in quantifying the cost reduction due to the *multitier* network design, as opposed to a single-tier network. Our study is motivated by the expected proliferation of personal communication services, which will serve different mobility platforms and support multimedia applications through a newly deployed infrastructure based on the multitier approach.

On Optimal Design of Multitier Wireless Cellular Systems

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Dealing with users of differing parameters will be a major challenge in future multimedia wireless networks. Examples of differing parameters include the mobile's speed, average number of received calls per unit of time, average required bandwidth per call, average call length, maximum allowed bit error rate, and permissible probabilities of call dropping and blocking [1–3].

The cellular systems for the next generation of wireless multimedia networks will rely on cells that are smaller than those used today. In particular, in the proposed microcellular systems, the cell radius can shrink down to as small as 50 m (0.5 mi — a 10-mi radius range for today's macrocellular systems). Smaller cell radii are also possible for systems with smaller coverage, such as pico- and nanocells in a local-area environment. The size of the cells is closely related to the expected speed of the mobiles that the system is to support (i.e., the faster the mobiles move, the larger the cells should be), to keep the complexity of handoffs at a manageable level. Furthermore, the cell size is also dependent on the expected system load (Erlangs per area unit); that is, the larger the system load, the smaller the cell should be. This is the direct outcome of the limited wireless resources (e.g., voice channels) assigned to handle cell traffic. Smaller cells result in channels being reused a greater number of times (i.e., greater extent of *concurrency*) and thus greater total system capacity. Finally, the cell size also depends on the required quality of service (QoS) level; for example, the probability of call blocking, of call dropping, or of call completion. In general, the more stringent the QoS, the smaller the cells need to be, since smaller cells increase the total system capacity. However, smaller cells translate to more base stations, and hence higher costs.

Systems utilizing more than one cell size have previously been proposed [4–6]. In particular, when there are multiple mobility classes, it is useful to consider *cell splitting*, which results in a multitier system [6]. For example, in a two-tier system, one tier consists of smaller cells (called *microcells* or *tier 2 cells*), which are used by low-mobility users, and the other of larger cells (called *macrocells* or *tier 1 cells*), used by high-mobility users. In this article, we employ the multitier idea to show how to optimize the design of a system with differing traffic requirements and mobile characteristics. Specifically, we examine how to lay out a multitier cellular system; given a total number of channels, the area to be covered, the average speed of mobiles in a tier, call arrival and duration statistics for each tier, and a constraint on the QoS (i.e., blocking and dropping probabilities), we show how to design a multitier cellular system in terms of the number of tier-*i* cells (e.g., of macrocells and microcells in a two-tier system) and the number of channels allocated to each tier so that the total system cost is minimized.

Because the objective is to minimize the cost of the multitier system subject to a minimum QoS constraint, there is an optimum cell size for every tier of the multitier system. The goal of this article is to determine these optimal cell sizes. Our study concentrates on the special case of a two-tier system, and we demonstrate that a two-tier approach results in substantially lower cost than the corresponding one-tier approach for the same QoS.

The article is organized as follows. In the next section, we discuss our network model. We then define the optimization problem and provide an algorithm for its solution. Numerical results for the example of a two-tier system are discussed, and we conclude with a brief discussion in the final section.

The Network Model

The network model assumed in our study is as follows. For each tier, the total area of the system (*coverage* area) is partitioned into cells. All cells of the same tier are of equal size. The network resources are also partitioned among the network tiers. Channels allocated to a particular tier are then reused based on the reuse factor determined for the mobiles of that tier[1] (i.e.,

[1] *The reuse factor is determined based on performance requirements, such as bit error rate for the digital system and a subjective test (mean opinion score) for analog voice systems. These requirements are translated into the required signal-to-interference ratio, which in turn determines the reuse factor.*

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within each tier, channels are divided into channel sets). One such set is then allocated to each cell of that tier. We use fixed channel allocation (FCA) for the allocation of channels both among the tiers and within a tier. We intend to study more dynamic allocation schemes [7, 8] in future work.

In this article, we address connection-oriented traffic only (i.e., our work does not cover the connectionless case), and we refer to a *call* as an association between a mobile and some other entity within the network. A call can be used to convey digital data, analog traffic, or digitized analog traffic, and thus requires allocation of the wireless resources.

Each tier is identified by several parameters:

- Call arrival rate
- Call duration time
- Call data rate
- Average speed of mobiles
- Performance factors
- QoS factors

The performance factors (e.g., bit error rate) determine the channel reuse plan [9]. The QoS factors used in this work are dropping probability and blocking probability. (Other factors have also been used in the literature, such as probability of call completion [4].) The probability of call blocking refers to an arriving call being denied service due to a lack of wireless resources. The probability of dropping accounts for calls in progress being terminated during the handoff process due to unavailability of wireless resources in the new cell. Of the two, call dropping is a more serious impairment. Consequently, network specifications call for a drop probability no greater than the blocking probability. As a simplifying assumption, we assume the same call data rate for all calls (i.e., a single channel allocation per call). We will study a more general case (e.g., that in [10]) in the future.

Additional assumptions regarding traffic modeling and the system architecture are as follows:

1. The traffic generation is spatially uniformly distributed.
2. Call arrivals follow a Poisson process. The spatial and time distribution of call arrivals are the same over all cells in a given tier, but can be different from tier to tier.
3. Call duration for a given tier is exponentially distributed, and may vary from tier to tier.
4. Handoffs and new calls are served from the same pool of available channels.
5. The speed of each class of mobiles is constant for each tier. We assume a mobility model similar to [13].
6. New call arrivals and call terminations are independent of the handoff traffic.

Note that assumption 4 means that, for a given tier, the probability of blocking equals the probability of dropping.

In this article, we formulate the multitier optimization problem as the minimization of the total system cost and propose an algorithm to evaluate the cost and calculate the design parameters of each tier. The system cost is composed of the cost of the base stations and interconnection of the base stations to the mobile switching center. The cost of a base station further consists of the equipment (electronics, tower, antennas, etc.), real estate (including the zoning rights to place wireless transmission equipment), installation costs, and operating, administrative, and maintenance costs. We do not dwell too much on the different cost components, noting that due to the large per-base-station cost, the total system cost is roughly proportional to the number of base stations [11]. The total system cost is the sum of the costs of all the tiers. We further assume that all base stations of a specific tier are of equal cost.

OPTIMAL DESIGN ALGORITHM

Notation:

A	Total area to be covered (m^2)
S	Number of tiers
C	Total number of available network channels
C_i	Number of channels allocated to tier i
N_i	Number of channels allocated to a tier i cell
f_i	Number of tier i cells in the frequency reuse cluster
m_i	Number of tier i cells contained in a tier $(i-1)$ cell. Tier 0 defines the total coverage area; $m_1 \stackrel{\text{def}}{=}$ total number of tier 1 cells.
R_i	Radius of a tier i cell (meters)
V_i	Average speed of tier i mobile users (meters per second)
λ_i^0	Number of tier i calls initiated per unit time per unit area: calls/(seconds · meter^2)
λ_i	Call initiation rate in a tier i cell (calls/s)
$1/\mu_i$	Average call duration of a tier-i cell (seconds per call)
h_i	Mean number of handoffs for a tier i call (handoffs per call)
γ_i	The relative cost of a tier i base station to the cost of a tier S base-station (i.e., $\gamma_S \equiv 1$)
$P_B(i)$	Actual blocking probability for a tier i cell
$P_D(i)$	Actual dropping probability for a tier i cell
$P_B^{max}(i)$	The maximum acceptable blocking probability for tier i calls
$P_D^{max}(i)$	The maximum acceptable dropping probability for tier i calls
$P_L(i)$	Loss probability of tier i
PLT	Overall system loss probability, weighted by the amount of traffic of each tier
PLT_{max}	The maximum acceptable weighted system loss probability
TSC	Total system cost
TSC_{max}	Maximum allowable total system cost; input design parameter tabbing

THE OPTIMIZATION PROBLEM

The objective of the work described in this article is to minimize the cost of the multitier infrastructure. In our model, we assume that the major part of the total system cost is the cost of base station deployment, which in our model is proportional to the total number of base stations. Thus, the total system cost, *TSC*, is:

$$TSC = m_1(\gamma_1 + m_s(\gamma_2 + m_3(\ldots))) = \sum_{i=1}^{S} \gamma_i \cdot \prod_{j=1}^{i} m_j, \quad S \geq 1. \tag{1}$$

In the above equation, we assume that cells are split in an arbitrary manner; that is, the location of tier i base stations is independent of the location of the base stations of the other tiers. In some cases, a more structured splitting may be used [5], in which cells of tier i form rings within a cell of tier $(i-1)$. An example is shown for the two-tier case in Fig. 1. Thus, if a base station already exists in a cell for tier i, the cost of placing an additional base station for a higher tier is negligible. Thus, for example, in the case of a two-tier network the total cost can be reduced by the cost of the tier 2 base stations. In such a case, the total cost is more accurately captured by the following formula:

$$TSC = \sum_{i=1}^{S} \gamma_i \left(\prod_{j=1}^{i} m_j - \prod_{j=1}^{i-1} m_j \right) = \gamma_1 m_1 + \sum_{i=2}^{S} \gamma_i (m_i - 1) \prod_{j=1}^{i-1} m_j, \; S \geq 1 \tag{2}$$

Reiterating some of the assumptions stated earlier, we assume that the set of all the available channels to tier i, C_i, is equally divided among the f_i cells in the frequency reuse cluster, leading to no channel sharing between the cells. Also, there is no channel sharing among the tiers. Furthermore, we assume that no channels are put aside for handling handoffs (i.e., allocation of channels for handoff requests and for new calls initiated within the cell are handled from the same pool of available channels in the cell).[2] Thus, the blocking and dropping probabilities are equal, and we term the probability of loss, $P_L(i)$; that is,

$$\forall i,\ P_L(i) = P_B(i) = P_D(i) \text{ and } P_L^{\max}(i) = \min\{P_B^{\max}(i), P_D^{\max}(i)\}.$$

The overall system loss probability, PLT is given by:

$$PLT = \frac{\sum_{i=1}^{S} P_L(i)\lambda_i^0}{\sum_{i=1}^{S}\lambda_i^0} \tag{3}$$

Our layout design problem is to minimize TSC, when the total number of available channels is at most C, and subject to the following QoS constraints:

$PLT \le PLT_{\max}$ and $\bar{P}_L \le \bar{P}_L^{\max}$.[3] In other words:

Determine $\{m_i\}$ minimizing TSC such that:

$$\sum_{i=1}^{S} C_i \le C \quad \text{and} \quad PLT \le PLT_{\max} \quad \text{and} \quad \bar{P}_L \le \bar{P}_L^{\max}. \tag{4}$$

Solution of the Optimization Problem

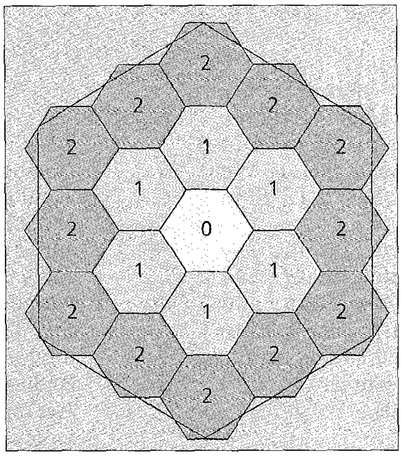
We first consider the average number of handoffs, h_i, that a call of tier i will undergo during its lifetime:

$$h_i = \frac{(3+2\sqrt{3})V_i}{9\mu_i R_i} \quad i = 1,2\ldots S \tag{5}$$

This expression was first derived in [13] for a one-tier system satisfying assumptions 1–6 above. However, since each tier is restricted to using the channels of the corresponding tier only, the expression is valid for our multitier system as well.

Now assume that there are a total of M_i cells in tier-i ($M_i = \Pi_{j=1}^{i} m_j$). Then the total average number of handoffs per second in all the cells is $h_i\lambda_i M_i$. The total arrival rate of handoff and initial calls in all tier i cells is $\lambda_i M_i (h_i+1)$, and the average total (handoffs and initial calls) rate per cell is

$$\lambda_i^{\text{total}} = \lambda_i(h_i + 1). \tag{6}$$



■ **Figure 1.** *Cell splitting.*

Note that in developing Eq. 6 we used assumption 6, together with the fact that the residual length of handed-off calls continues to be exponentially distributed [13]. Thus, the total arrival process to a cell is still Markovian, with the average rate of λ_i^{total}. Since the area of a hexagon with radius R is $3\sqrt{3}/2R^2$, we obtain

$$\lambda_i = \lambda_i^0 \frac{3\sqrt{2}}{2} R_i^2. \tag{7}$$

This leads to

$$\lambda_i^{total} = \lambda_i^0 R_i \frac{[(2+\sqrt{3})V_i + 3\sqrt{3}\mu_i R_i]}{2\mu_i} \tag{8}$$

The average call termination rate (based on [13]) is

$$\mu_i^{\text{total}} = \mu_i(1 + 9h_i). \tag{9}$$

We are now ready to consider the call loss probability. Based on assumptions 1–4, we can use the Erlang-B formula [12] extended to $M/G/c/c$ systems.[4] The probability of loss of a tier i call is therefore

$$P_L(i) = \frac{(\lambda_i^{\text{total}}/\mu_i^{\text{total}})^{N_i}/N_i!}{\sum_{j=0}^{C_i}(\lambda_i^{\text{total}}/\mu_i^{\text{total}})^j/j!} = \frac{\{[\lambda_i(1+h_i)]/[\mu_i(1+9h_i)]\}^{N_i}/N_i!}{\sum_{j=0}^{C_i}\{[\lambda_i(1+h_i)]/[\mu_i(1+9h_i)]\}^j/j!},\ i = 1,2,\ldots S. \tag{10}$$

where λ_i^{total} and μ_i^{total} are given by Eqs. 8 and 9, respectively, λ_i and h_i by Eqs. 7 and 5, respectively, and

$$N_i = \left\lfloor \frac{C_i}{f_i} \right\rfloor, \quad i = 1,2,\ldots,S. \tag{11}$$

In the rest of the article, we assume a two-tier system ($S = 2$). Then the cost function in Eq. 2 simplifies to

$$TSC = \gamma_1 \cdot m_1 + \gamma_2 \cdot m_2 \cdot (m_2 - 1) \tag{12}$$

We will now express m_1, m_2, and R_2 as a function of the area, A, and the tier 1 cell radius, R_1. We have

$$m_1 = \left\lceil \frac{A}{\text{Area of tier-1 cell}} \right\rceil = \left\lceil \frac{2\sqrt{3}A}{9R_1^2} \right\rceil \tag{13}$$

We assume that both tier 1 and tier 2 cells are hexagonally shaped and that tier 2 cells are obtained by suitably splitting the tier 1 cells. Each tier 1 cell will contain k layers of tier 2 cells. Figure 1 shows an example of a tier 1 cell which contains three layers (0, 1, and 2).

From the geometry of a hexagon, the number of tier 2 cells in a tier 1 cell is given by

$$m_2 = 1 + 6 + \cdots + 6k = 1 + 3k(k + 1), \quad k = 0, 1, \ldots, \tag{14}$$

where $(k + 1)$ denotes the number of "circular layers" in the cell splitting. Also, the radius of a tier-2 cell is given by

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[2] *This is the way that most first and second generation wireless systems work.*

[3] *Note that our constrains include both the average probability of loss, as well as the individual tiers' probability of loss. This is to ensure that every mobile enjoys at least some minimal quality of service and that the overall system performance is also satisfactory, by giving more weight to the more populated tiers.*

[4] *Erlang-B formula which applies to an $M/M/c/c$ queueing system is also valid for an $M/G/c/c$ system [14].*

Parameter	Value/range	Units
A	100	km^2
C	90	Channels
S	2	
λ_1^0	0.2–3.0	Calls/(min · km^2)
λ_2^0	5.0–40.0	Calls/(min · km^2)
μ_1, μ_2	0.33	Calls/min
γ_1	10.0	\$ (in 1000s)/base
γ_2	1.0	\$ (in 1000s/base
V_1	30–540	km/hr
V_2	1.5–12.0	km/hr
f_1, f_2	3	
TSC_{max}	10,000–20,000	\$ (in 1000s)
PLT_{max}	0.01	
$P_B^{max}(*)$	0.01	
$P_D^{max}(*)$	0.01	

■ **Table 1.** *Parameter values.*

$$R_2 = \frac{R_1}{\sqrt{m_2}}. \tag{15}$$

Our optimization problem can be solved by using Eqs. 10–15 through a search algorithm with pruning, as described in the next section.

Layout Algorithm

We next present the search procedure for a two-tier cellular system. The constrained optimization problem outlined above consists of finding optimal values of R_1, R_2, C_1, C_2, m_1, and m_2, which are the system design parameters. We label the optimal values R_1^*, R_2^*, C_1^*, C_2^*, m_1^*, and m_2^*. The parameters m_1, m_2, C_1, and C_2 are integers, while R_1 and R_2 are continuous variables. However, we only need to consider a discrete subset of the possible values of R_1. From Eq. 13, we can see that it is sufficient to consider just those values of R_1 for which

$$R_1 = \sqrt{\frac{2\sqrt{3}A}{9\ell}}$$

where $\ell = m_{\min 1}, \ldots, m_{\max 1}$. $m_{\min 1}$ and $m_{\max 1}$ are the lower and upper bounds, respectively, of the number of tier 1 cells in the system. Thus, R_1 can only assume one of $m_{\max 1} - m_{\min 1} + 1$ values.

The lower bound, $m_{\min 1}$, is usually assumed to be equal to 1, while the upper bound, $m_{\max 1}$, can be estimated from TSC_{max}, which is given to the designer, in the following way:

$$m_{\max 1} = \left\lceil \frac{TSC_{\max}}{\gamma_1} \right\rceil. \tag{16}$$

We use the following search procedure to find the design parameters.

$TSC^* = TSC$

$$m_{\max 1} = \left| \frac{TSC_{\max}}{\gamma_1} \right|$$

$$a_1 = \frac{3\sqrt{2}}{2}\lambda_1^0$$

$$a_2 = \frac{3\sqrt{3}}{2}\lambda_2^0$$

$$b_1 = \frac{3+2\sqrt{3}}{9\mu_1}V_1$$

$$b_2 = \frac{3+2\sqrt{3}}{9\mu_2}V_2$$

$$c = \sqrt{\frac{2\sqrt{3}A}{9}}$$

while $(m_{\min 1} \le m_1 \le m_{\max 1})$ do

$R_1 = \frac{c}{\sqrt{m_1}}$

$\lambda_1 = a_1 R_1^2$

$h_1 = b_1/R_1$

while $(1 \le C_1 < C)$ do

$$N_1 = \left\lfloor \frac{C_1}{f_1} \right\rfloor$$

$$N_2 = \left\lfloor \frac{C - C_1}{f_2} \right\rfloor$$

$$P_L(1) = \frac{\{[\lambda_1(1+h_1)]/\mu_1(1+9h_1)]\}^{N_1}/N_1!}{\sum_{j=0}^{N_1}\{[\lambda_1(1+h_1)]/[\mu_1(1+9h_1)]\}^j/j!}$$

for $(k=1;\,;k{+}{+})$ do

$m_2 = 1 + 3k(k+1)$

$TSC = \gamma_1 \cdot m_1 + \gamma_2 \cdot m_1 \cdot (m_2 - 1)$

if $(TSC > TSC^*)$ then break

$R_2 = R_1/\sqrt{m_2}$

$\lambda_2 = a_2 R_2^2$

$h_2 = b_2/R_2$

$$P_L(2) = \frac{\{[\lambda_2(1+h_2)]/\mu_2(1+9h_2)]\}^{N_2}/N_2!}{\sum_{j=0}^{N_1}\{[\lambda_2(1+h_2)]/[\mu_2(1+9h_2)]\}^j/j!}$$

$$PLT = \frac{\lambda_1^0 P_L(1) + \lambda_2^0 P_L(2)}{\lambda_1^0 + \lambda_2^0}$$

if $((PLT < PLT_{\max})$ and $(P_L(1) < P_L^{\max}(1))$ and $(P_L(2) < P_L^{\max}(1)))$ then break

end for

if $(TSC < TSC^*)$ then

$\hat{k} = k$

$m_1^* = m_1$

$m_2^* = m_2$

$R_1^* = R_1$

$R_2^* = R_1/\sqrt{m_2}$

$C_1^* = C_1$

$C_2^* = C - C_1$

end if

end while

end while

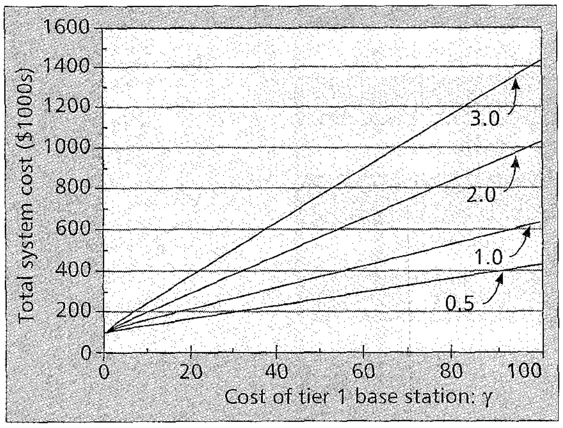
The outputs of the algorithm are: TSC^*, m_1^*, m_2^*, R_1^*, R_2^*, C_1^*, and C_2^*.

Numerical Examples

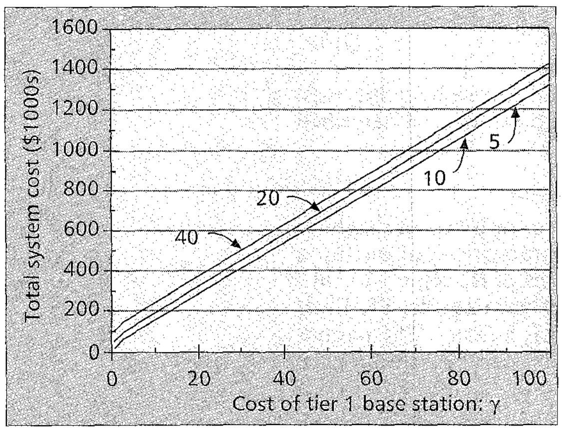
In this section we report selected performance figures of two-tier systems and their comparison with the corresponding single-tier systems. We used the proposed algorithm to generate numerical results for systems with the parameter ranges found in Table 1.

The speeds of tier 1 mobiles were taken to represent vehicular and airplane traffic, while tier 2 speeds are representative of pedestrian and cycling traffic.

First, we investigated the effect of γ on the total system cost for different parameters. In Fig. 2 the parameter is the tier 1 call density, while in Fig. 3 the parameter is the tier 2 call density. The tier 1 and tier 2 average speeds were 90 km/hr and 3 km/hr, respectively. The $TSC_{\max}$ was taken as \$20,000*K*. As γ increases, the total system cost (as well as the number of tier 2 base stations) increase, since for more expensive tier 1 base stations there tend to be fewer of these, resulting in more channels being allocated to tier 1 cells to satisfy the tier 1 QoS. This results in fewer channels available to tier 2 cells, which requires larger channel reuse, smaller tier 2 cells, and thus more tier 2 base stations. Also as expected, the effect of λ_1^0 and λ_2^0 on the total system cost (and the number of tier 2 base stations) is nonlinear (i.e., the increase in cost for the same relative increase in call density is larger for larger values of call densities), due to the effect of the total call arrival on the probability of loss in the Erlang-B formula.

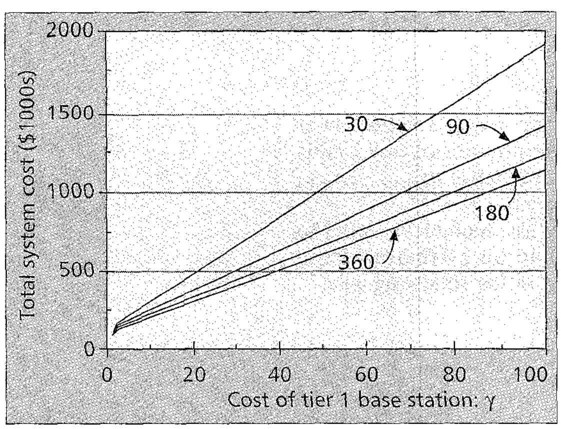


■ **Figure 2.** *The effect of γ on total system cost (labels indicate λ_1^0).*



■ **Figure 3.** *The effect of γ on total system cost (labels indicate λ_2^0).*

Figures 4 and 5 show the effect of γ on the total system cost, where the average speeds of tier 1 and tier 2, respectively, are the parameters. For these graphs, the call arrival densities were taken as λ_1^0 = 2[calls/(min · km^2)] and λ_2^0= 10[calls/(min · km^2)] and $TSC_{\max}$ = \$10,000*K*. It is interesting to note that for our practical range of parameters, the total normalized cost is much more sensitive to the speed of tier 1 mobiles than to that of tier 2 mobiles for the same relative change in the mobiles' speed. This is especially true for large values of γ. This behavior can be explained by the fact that the amount of handed-off traffic for the tier 1 system is considerably greater than for the tier 2 system. Thus, the same relative increase in total handoff traffic has a considerably greater effect on the system working at high utilization, as is tier 1.



■ **Figure 4.** *The effect of γ on total system cost (labels indicate V_1).*

We will next compare the performance of the two-tier system with a one-tier system. To obtain results for a one-tier system we ran the optimization algorithm with $R_1 = R_2$. This results in both tiers sharing the same cells and $m_2 = 1$. The total cost is then computed as $TSC = m_1\gamma_1$.

Figure 6 depicts the total system cost as a function of tier 2 mobiles' speed, while tier 1 mobiles' speed is fixed for a one-tier and a two-tier system. Tier 1 mobiles' speeds considered are 30, 90, 180, 270, 360, and 540 km/hr. The two-tier system is far expensive than the one-tier system.

We notice that for a constant tier 1 speed, TSC is relatively stable as a function of tier 2 speed. This is due to the relatively large volume of tier 1 handoff traffic, which dominates the channel assignment to tier 1 cells. This is not the case in the single-tier system, since as the speed of the slower mobiles increases and the cell size is constrained by the faster mobiles, the total handoff traffic for the slower mobile class requires assignment of more channels to the faster mobile class. This results in a larger number of cells and increases the total system cost. Finally, the main conclusion from Fig. 6 and many other similar runs is that, for the parameter ranges used in this study, the two-tier system outperforms the single-tier system for all the values of the slower and faster mobiles' speeds.

Discussion

Multitier architectures are economical in situations where there are mobiles characterized by different mobility patterns, running applications with different QoS requirements, and having substantially different call arrival density and average holding time.

In this article, we have considered the optimal design of a multitier system to minimize the total system cost. We define system cost as being primary composed of the cost of cell sites (i.e., the base stations) and develop a procedure to determine the cell sizes for each tier, the portion of the total number of channels assigned to each tier, and the total system cost. A system designer can use the proposed algorithm to estimate the total system cost and to determine the required number of cells for each tier and the partition of the system channels among the tiers.

Our numerical results indicate that two-tier systems outperform their one-tier counterparts for the range of design parameters considered here. Another lesson learned from the numerous cases we have studied is that the performance degradation of the two-tier systems is much more gradual than that of one-tier systems. We believe this conclusion can be carried over to the general case of multitier systems.

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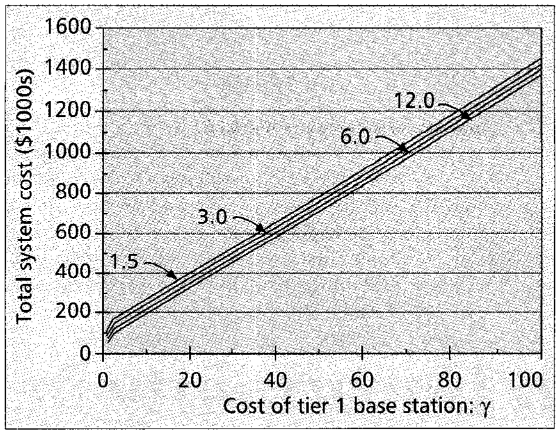
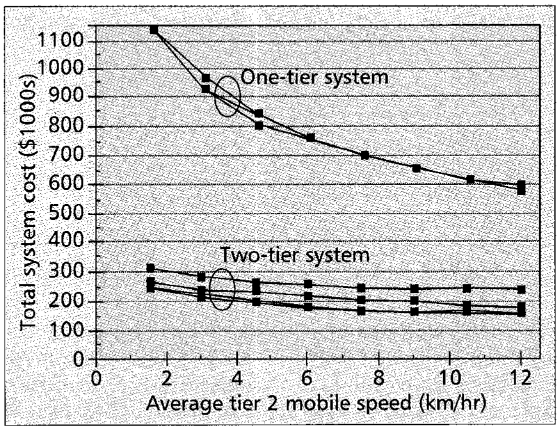


■ **Figure 5.** *The effect of γ on the total system cost*



■ **Figure 6.** *Comparison of the total system costs between the one-tier and two tier-systems, λ_1^0 = 1[calls/min · km^2)] and λ_2^0 = 20 [calls/(min · km^2)].*

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