Trends in Handover Design

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The author presents an overview of published work on handover performance and control and discusses current trends in handover research.

Handover[1] is the mechanism that transfers an ongoing call from one cell to another as a user moves through the coverage area of a cellular system. As smaller cells are deployed to meet the demands for increased capacity, the number of cell boundary crossings increases. Each handover requires network resources to reroute the call to the new base station. Minimizing the expected number of handovers minimizes the switching load. Another concern is delay. If handover does not occur quickly, the quality of service (QoS) may degenerate below an acceptable level. Minimizing delay also minimizes co-channel interference. During the handover there is a brief service interruption. As the frequency of these interruptions increases the perceived QoS is reduced. The chances of dropping a call due to factors such as the availability of channels increase with the number of handover attempts. All of these issues place additional challenges on the cellular system. As the rate of handover increases, handover algorithms need to be enhanced so that the perceived QoS does not degenerate and the cost to the cellular infrastructure does not skyrocket. Much effort is being expended to study existing handover schemes, and to create new ones that meet these challenges.

This article presents a survey of published work on handover performance and control. The aim is not to describe each approach in detail but to present the flavor of current trends in handover research. What types of approach are taken? How do the system assumptions differ? An introduction into the metrics that provide a base for quantitative comparisons is the starting point for a discussion of the basic schemes used to initiate a handover. Adjustments can be made to these schemes to control the handover process. The optimum settings change with shrinking cells and with varying propagation characteristics.

The deployment of a multitier system with macrocells overlaying microcells offers system providers new opportunities. Clever uses of the two tiers can lead to increased end-user performance and system capacity. For example, stationary users can be assigned to microcells so that they operate at reduced power and cause significantly less interference; when the microcellular capacity is exhausted, the overflow traffic can be assigned to the macrocells. Approaches such as this create a whole new area for investigation. Should pedestrians use microcells and vehicles use macrocells? Should speed, assuming we can determine it, be the determining factor in assigning a user to a particular tier? Alternately, the same variables used to control handover in single-tier systems may be augmented to provide the additional functionality needed to control cross-tier handovers. Perhaps the existing control variables are adequate by themselves, and all that is needed are novel techniques to set their values differently. Does an algorithm need to know whether a user is in the macrocell or microcell plane to interpret measurements of the current and candidate base stations? Do the macrocells and microcells use the same radio link and network protocols? Do adjacent system providers use the same radio link and network protocols in either the macrocellular and/or microcellular tiers? Finally, once a system provider chooses a particular algorithm, say for radio link efficiency, does it adversely impact the teletraffic performance of the system? That is, are all users shuffled into one tier while the other tier remains underutilized?

This article discusses the status of various aspects of this work. The presentation is divided into two parts. The first section discusses investigations that are applicable to a single tier of cells. It focuses on macrocells, but includes a brief discussion on how things change as cell sizes shrink. The second part assumes an overlay of macrocells and microcells and summarizes issues and approaches unique to such systems. The article concludes with a summary overview. An extensive bibliography is included to allow the reader to further explore the subject.

HANDOVER BASICS

This section provides background information on traditional topics in handover research. A list of common performance metrics is followed by a description of the methods commonly used to initiate a handover. These form the basis for many investigations into microcellular handover and overlaid system handover. The control aspects of handover, that is, the way in which a system provider can tune the performance of a handover algorithm, are then discussed. Finally, a brief overview is included of those aspects that require special attention as cells shrink.

[1] *The terms "handover" and "handoff" are used interchangeably within the literature.*

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Performance Metrics

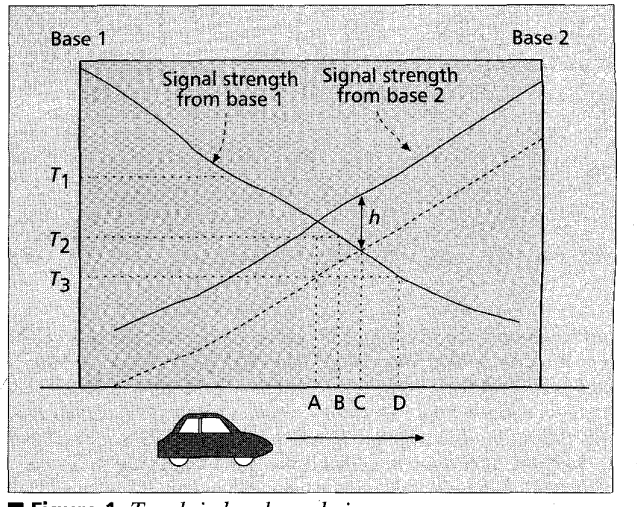
This subsection discusses basic performance aspects of handover. The performance metrics used to evaluate handover algorithms [1, 2]) are:

- *Call blocking probability* — the probability that a new call attempt is blocked.
- *Handover blocking probability* — the probability that a handover attempt is blocked.
- *Handover probability* — the probability that, while communicating with a particular cell, an ongoing call requires a handover before the call terminates. This metric translates into the average number of handovers per call.
- *Call dropping probability* — the probability that a call terminates due to a handover failure. This metric can be derived directly from the handover blocking probability and the handover probability.
- *Probability of an unnecessary handover* — the probability that a handover is stimulated by a particular handover algorithm when the existing radio link is still adequate.
- *Rate of handover* — the number of handovers per unit time. Combined with the average call duration, it is possible to determine the average number of handovers per call, and thus the handover probability.
- *Duration of interruption* — the length of time during a handover for which the mobile terminal is in communication with neither base station. This metric is heavily dependent on the particular network topology and the scope of the handover [3].
- *Delay* — the distance the mobile moves from the point at which the handover should occur to the point at which it does.

Handover Initiation

A hard handover, as opposed to a soft handover, occurs when the old connection is broken before a new connection is activated. Published performance evaluations of hard handover study several initiation criteria. All assume the signal is averaged over time to remove the rapid fluctuations due to the multipath nature of the radio environment. Detailed studies have been done to determine the shape as well as the length of the averaging window, that is, how much we should trust older measurements. Figure 1 shows a mobile moving from one base station (base 1) to another (base 2). The averaged signal strength of base 1 decreases as the mobile moves away from it. Similarly, the averaged signal strength of base 2 increases as the mobile approaches it. Using this figure, the following discussion explains various approaches:

- *Relative signal strength* chooses the strongest received base station at all times. The decision is based on an averaged measurement of the received signal. In Fig. 1, the handover will occur at position A. This method is shown to stimulate too many unnecessary handovers when the current base station signal is still adequate [1].
- *Relative signal strength with threshold* allows a user to hand over only if the current signal is sufficiently weak (less than a threshold) and the other is the stronger of the two. The effect of the threshold depends on its value compared to the signal strengths of the two base stations at the point at which they are equal. If the threshold is higher than this value, say T_1 in Fig. 1, this scheme performs exactly like the relative signal strength scheme, so the handover occurs at position A. If the threshold is lower than this value, say T_2 in Fig. 1, the mobile will delay handover until the current signal level crosses the threshold at position B. In the case of T_3, the delay may be so long that the mobile drifts far into the new cell. This reduces the quality of the communication link and may result in a dropped call. In addition, this causes additional interference to co-channel users. Thus, this scheme may create overlapping cell coverage areas. A threshold is not used alone in practice because its effectiveness depends on prior knowledge of the crossover signal strength between the current and candidate base stations.



■ **Figure 1.** *Trends in handover design.*

- *Relative signal strength with hysteresis* allows a user to hand over only if the new base station is sufficiently stronger (by a hysteresis margin, h, in Fig. 1) than the current one. In this case the handover will occur at point C. This technique prevents the so-called *ping-pong effect*, the repeated handover between two base stations caused by rapid fluctuations in the received signal strengths from both base stations. The first handover, however, may be unnecessary if the serving base is sufficiently strong.
- *Relative signal strength with hysteresis and threshold* hands a user over to a new base only if the current signal level drops below a threshold and the target base station is stronger than the current one by a given hysteresis margin. In Fig. 1, the handover will occur at point C if the threshold is either T_1 or T_2, and will occur at point D if the threshold is T_3.
- *Prediction techniques* base the handover decision on the expected future value of the received signal strength. A technique is proposed and shown via simulation to be better, in terms of a reduction in the number of unnecessary handovers, than both the relative signal strength and relative signal strength with hysteresis and threshold methods [4].

In summary, handover initiation criteria analyzed in the literature are based on essentially four variables: the length and shape of the averaging window, the threshold level, and the hysteresis margin. Techniques that control handover initiation using these criteria are discussed in the following subsection.

After choosing a new base station, a user may then choose a channel at that base. Some algorithms implement base and channel selection as a single decision, and often denote it as *joint base station and channel assignment*. One such study simulates a signal-to-interference-ratio-(SIR)-based handover algorithm for a one-dimensional system [5]. Subsequently, they use the same simulation tool to evaluate the *maximum power handover* (*MPH*) scheme, a variant of the relative signal strength method that includes multiple handover candidates [6]. As compared to the SIR-based handover, for a slight increase in call blocking MPH shows a notable decrease in call dropping at the expense of an increase in the number of

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	Vijayan *et al.* [13, 14]	Zhang *et al.* [16]	Corazza *et al.* [15]
Hysteresis margin	X	X	X
Threshold level		X	
Averaging interval	X		X
Window shape			X

■ **Table 1.** *Overview of handover control studies.*

unnecessary handovers and ping-pongs. To correct this problem a timer is introduced into the MPH scheme to create a new scheme, *maximum power handover with timer* (*MPHT*). A handover is allowed only after a timer expires. It is shown that this decreases the number of unnecessary handovers relative to MPH, but has little effect on call blocking or dropping. This work has been extended to two-dimensional systems [7].

Thus, both hysteresis margins and timers can be used to reduce the ping-pong effect. In the Pan-European Digital Cellular Standard [8], a *handover margin* parameter is used as the hysteresis margin. In addition, there is a *temporary offset* controlled by a timer to favor intracell handovers over intercell handovers whenever possible. The North American Personal Access Communications System (PACS) personal communications services (PCS) standard [9] combines the hysteresis margin with a *dwell timer*. No work has been published reporting on the performance of a combined hysteresis and timer-based handover procedure.

Reward/cost optimization techniques have been applied to study handover [10]. A reward is given for maintaining a connection, and there is a cost associated with switching a connection. This methodology is very preliminary and has not yet been applied to real systems.

Propagation modeling of a connection with a satellite has been compared with that from a land station [11]. It is noted that handover between satellites is more complicated than handover between a land station and a satellite. No protocols are discussed and no justification is given for this argument. For an intermediate circular orbit (ICO) satellite (i.e., one at 6000–20,000 km) a typical voice call may not require any handover at all [12]. No such claims were made for low earth orbit (LEO) satellites, which revolve at an elevation of less than 2000 km. It is quite possible that for LEO satellites user mobility is not an issue at all. In the Iridium proposal the footprints of the satellites move across the earth at a speed of 7 km/s. Thus users, even highly mobile ones, seem to be standing still.

Another important issue in satellite deployment is the elevation off the horizon, the grazing angle. Low-grazing-angle satellites have larger footprints and therefore require less frequent handovers. High-grazing satellites deliver a better-quality signal. A study with parameters taken from the LEO Iridium and ICO LEONET concepts [12] reveals that the gain in quality does not justify the reduction in footprint size.

Initiation Control

Parameters under the control of the designer include the hysteresis margin, threshold level, averaging interval, window shape, and dwell timer. Table 1 shows the subsets of these control parameters that various authors have chosen to study.

The hysteresis margin and the duration of averaging can be used [13] to trade off the mean number of handovers against the delay in handover. The handover process was studied in terms of the level crossing process of the difference in received signals between the two base stations, where mobiles move on a straight line between them. At first the level crossing process was assumed to be stationary; later work [14] included the nonstationary case. A simulation study [15] evaluated the trade-off between delay and number (and probability) of unnecessary handovers. Parameters again included the hysteresis level and the averaging window length. This work focused on the shape of the averaging window, and considered both rectangular windows and exponential windows with various weights. Long windows reduce the number of handovers but increase the delay.

The analytic work on handover algorithm performance is extended [16] from the case of relative strengths to the case of combined absolute and relative strengths. With the averaging interval fixed, results report on the tradeoff between delay and the expected number of handovers. Figure 2 shows the method of reporting these results. The y-axis shows the average number of handovers that occur while a user is moving from base 1 to base 2 in Fig. 1. The x-axis shows the location of the first handover between Base 1 and Base 2, where 0.50 indicates that it occurs at the halfway point and 0.75 means the mobile is 75 percent of the way to Base 2. For a particular set of values for the hysteresis margin, h, and the threshold level, T, the system will operate at the point marked A. The horizontal distance from $x = 0.5$ and the location of A is a measure of the handover delay. Figure 2 shows that as either the hysteresis margin is increased or the threshold level lowered, the mean number of handovers decreases as the expected delay increases.[2] When the hysteresis level is small for the considered parameters, the threshold has a greater influence on the expected number of handovers and crossover point [16]. Careful inspection of Fig. 1 reveals that this is related to which trigger (threshold or hysteresis) occurs first. The hysteresis level can be used to trade the number of handovers against delay; this relation is plotted on a single curve for several thresholds, and the exact position on the curve depends on the threshold.

A soft handover algorithm is modeled [17] using techniques proposed for conventional handover algorithms [16]. Given a system with two base stations, a user is in communication with either one or both of them. A user in communication with both is in soft handover and is said to be in the active set. Each user in an active set requires fixed network resources to deliver the speech information to the mobile switching center (MSC). The trade-off is between the number in the set and the number of active set updates. Users are added to the set when their signal crosses a threshold, and removed from the set when they are below another threshold for a period of time that exceeds a timer. It is shown that this timer greatly decreases the number of updates to the active set while only slightly increasing the average size of the set.

Various other topics in handover control include a discussion of priority handover schemes [18]. This work is motivated by the fact that the best strategy for the radio link in terms of minimizing the number of handovers may not work well from a teletraffic point of view in the case of hot spots, areas of dense traffic. Users may be dropped due to an algorithm which denies additional handover attempts that may save the call. Results advocate reserving radio channels for handover.

The application of nonstandard approaches to handover control include neural networks, fuzzy logic, hypothesis testing, and dynamic programming. Neural networks are proposed as a possible tool to implement multicriteria handover algorithms [19]. A simple example illustrates the methodology but requires significant background knowledge on neural networks. It is noted that when the neural network approach con-

[2] *Note that all pairs of* h *and* T *may not lay exactly on a single line, but results [16] show that they "cluster" very closely near by.*

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trols handover, microcell/macrocell overlays "may have little effect on the handover implementation" [19]. The number of handovers can be reduced by using various fuzzy logic and pattern recognition techniques [20]. This article simulates the case of three cells for various techniques and reports reductions in the number of handovers of 5–7 percent. A signal-strength-based neural network mobile-controlled handover algorithm based on hypothesis testing is also proposed [21]. No performance results are given to show that it is better than existing algorithms, but they are reportedly forthcoming. A dynamic programming treatment of a handover algorithm that minimizes service failures as well as the number of handovers results in a strategy with performance essentially the same as the classic hysteresis-threshold strategy [22]. A service failure occurs when the signal strength falls below a certain level required for satisfactory service but not sufficiently poor to drop a call.

Microcellular Handover

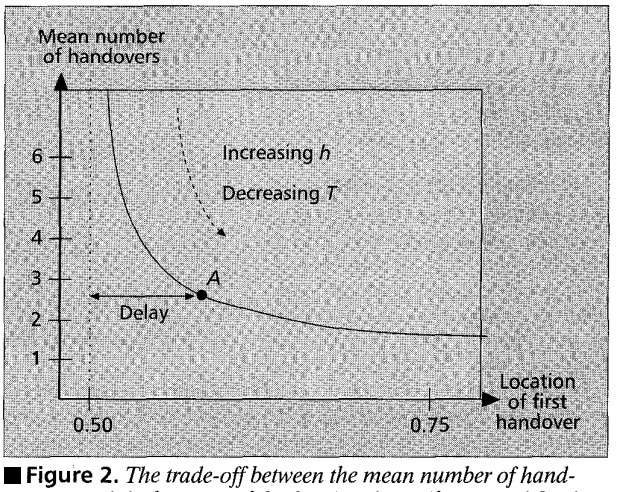
The use of a GSM-like mobile-assisted handover in a microcellular environment is studied in terms of radio propagation issues [23]. The rapid change in the received signal strength when a mobile turns a corner, the corner effect, is shown to affect the uplink more than the downlink in a microcellular environment. This is based on the observation that when a mobile turns a corner, the signal gets weaker while the uplink interference remains constant and the downlink interference changes, potentially getting weaker. The signal measurements as users cross intersections and turn corners are studied via simulation [24].

A distinction is made between line-of-sight (LOS) handover, when the two base stations can see each other, and non-LOS handover, when they cannot. In the LOS case, hysteresis may be useful in preventing premature handover requests at the expense of possible delay [25]. It is concluded [24] that a handover decision should be based on both the upstream and downstream measurements. This will reduce the number of handovers to non-LOS base stations that become visible when crossing an intersection. In a macrocellular environment with cells over 600 m, the slope of the received power with distance is flatter near the equipower midpoint between two base stations [25]. Thus, hysteresis will significantly delay the handover initiation process.

There are two contradictory goals. LOS handover avoids the ping-pong effect, whereas non-LOS handover must be done as quickly as possible due to the sudden signal drop as a mobile turns a corner [23]. Possible solutions to these contradictory goals include the use of umbrella cells, the use of macrodiversity, and switching to mobile-controlled handover [23]. Only the umbrella cell approach provides compatibility with existing standards.

The performance of simulcasting in the downlink is analyzed and compared to selection diversity [26]. While simulcasting improves the robustness of a user's signal to fading, the effect on other users needs to be investigated. Results quantify the co-channel interference performance of simulcasting with both coherent and noncoherent receivers. In both cases, carefully designed simulcasting algorithms can reduce the effects of co-channel interference.

The handover decision process is studied for a microcellular Manhattan grid. The choice of reuse pattern affects the upstream and downstream SIR measurements [24]. Moving from a seven-cell reuse deployment with omnidirectional antennas to a three-sector system with a reuse of 3 increases the capacity by a factor of 7/3 but reduces the maximum number of channels in a single location by a factor of 7/9 [27]. This article proposes a cell layout with macroscopic diversity



■ **Figure 2.** *The trade-off between the mean number of handovers and the location of the first handover (fraction of the distance between two identical base stations) is controlled jointly by the hysteresis margin,* h, *and the threshold level,* T.

and overlaid cells that increases the capacity by a factor of 7/3, and also increases the maximum number of channels in a single sector by a factor of 7/3. This is achieved by accepting a less steep decline in power at the boundary between two cells, which complicates the handover decision and causes it to require other information besides signal strength. Recall from the earlier discussion that a less steep decline will cause additional delay assuming that the hysteresis margins remain fixed.

Microcells can be deployed along with macrocells to handle pockets of dense traffic. The available spectrum can either be divided or shared between the two classes of cells. The divided spectrum method avoids macrocell/microcell interference problems but is spectrally inefficient unless the location of all users is known in advance. Spectrum sharing can be achieved via either disjoint or overlaid microcells and macrocells.

Spectrum sharing is easier in the case when the traffic is not uniformly distributed [28]. If microcells are deployed to cover a hot spot surrounded by a lower traffic area, one may envision a system with both microcells and macrocells, each covering a disjoint area. Special attention must be given to the channels assigned to the microcells along the border of the microcellular region.

Several overlaid fixed channel plans, with different reuse distances, may be dynamically allocated channels based on the location of mobiles. If mobiles are close to the base station they are assigned a channel from a group with a lower reuse distance. Performance bounds on this strategy are derived [29]. A channel segregation dynamic channel assignment (DCA) system is proposed [30] which reuses the same channels in the microcells that are used in the macrocells. Macrocell-to-microcell interference is compensated for by a slight increase in microcell transmit power.

Macrocell/Microcell Overlays

This section provides an overview of issues related to an overlaid system of microcells and macrocells. First, the control issues related to an overlaid system are discussed in two sections. The first uses velocity estimation as an assignment criterion; the second considers approaches that propose slightly different ways of using the same control parameters as single-tier systems. Then the problem of system integration is introduced: what to do when the macrocellular and microcellular systems use different radio link standards? Finally, the teletraffic implications of such a system are discussed. Does

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the multitier system distribute traffic effectively and deliver the promised QoS requirements?

Velocity Estimation

Microcell/macrocell system proposals often assign users to a particular level according to their speed. Fast users are generally encouraged to join macrocells, and slow users typically join microcells. Users are then instructed to move between the microcellular and macrocellular planes based on their speed. This jointly reduces the number of handovers and increases the total system capacity. This section provides an overview of several velocity-based assignment algorithms and then highlights some of the velocity estimation methods.

Users may prefer the microcells unless no capacity is available or they are moving too quickly [31]. On the other hand it may be appropriate to immediately place slow users in the microcells and fast users in the macrocells and allow handovers between cell layers as needed [32]. Another approach initiates calls via the macrocell [33]. A user must remain in a macrocell for a sufficiently long time before being handed over to the microcell plane. After exceeding this interval, the user is directed to the microcell in which it was located when the call began, assuming that the user did not exit that microcell. An extension to this technique estimates a user's speed at a given point prior to entering the cell; this allows the system to assign users more quickly after they cross into the cell. Thus, in all cases sufficiently slow users are more likely to be assigned to a microcell than are fast-moving users.

Estimation of vehicle velocity is possible if its receiver's Doppler frequency is known. There is a useful relationship between the branch switching rate of a diversity receiver and its Doppler frequency which permits the estimation of vehicle speed without any significant hardware changes [34]. Three methods of velocity estimation — level crossing rates, zero crossing rates, and a covariance method — have been compared using physical layer considerations [35]. Their performance differs depending on the propagation environment. Understanding how the velocity estimators react to changes in the propagation environment allows their use for detecting when a mobile turns a corner.

Direction-biased algorithms are proposed and studied via simulation [36]. Four base stations are compared at the point of handover. Hysteresis levels are used to favor approaching over receding base stations. Alternately, it is possible to preselect a direction of motion and choose a base station in that direction. Results show that in addition to an improvement in cell membership properties, there is a reduction in the number of handovers as well in the handover delay. An exact solution for the cost formulation in [36] is developed using a Markov decision process [37]. The model involves only two base stations, assumes available channels, and neglects cochannel interference; thus, this work is mainly of theoretical interest. Furthermore, the conclusion that a threshold policy is optimal may be the result of an oversimplified model.

An extension to the Global System for Mobile Communications (GSM) [32] employs a variable hysteresis threshold which depends on a user's mobility. In particular, user mobility is estimated from the time spent in a cell. A three-level hierarchical cellular system is studied [38]. Each cell covers an area covered by seven cells at the next lower level. Users should be assigned to an appropriate level according to an estimate of their speed based on the cell dwell times. Four strategies are compared:

The FDMA, TDMA, and CDMA techniques can be combined in various ways. A system such as GSM is a combined TDMA/FDMA system.

- Move to a bigger cell if the user does not spend enough time in the current cell
- Do this, but also move to a smaller cell if the user stays there too long
- Estimate speed using a maximum likelihood estimator
- Estimate speed using a minimum mean square estimator.

The number of handovers is the performance metric. The latter two alternatives yield essentially the same results. At high loads all are essentially the same; at low loads the latter strategies outperform the earlier ones.

Multitier Control

The criteria for handover in a macrocellular and microcellular environment may differ. There are two common methods employed to control handover in a multitier environment. Handover measurements are averaged over a fixed time interval to remove short-term variations. The averaged handover measurement of a candidate cell must exceed the current cell by at least a fixed hysteresis level. It is suggested that, in macrocellular systems with relatively gentle pathloss characteristics, the averaging interval should be large enough to remove the variations due to fading [39]. A large hysteresis value is never desirable because it increases delay in cases of moderate fading. For microcellular systems a long averaging interval is not desirable due to the sudden path loss that results from the corner effect; the hysteresis should be chosen high enough to avoid being fooled by the fading characteristics. In a combined micro- and macrocellular system both criteria should be used. The first one to detect a handover will depend on the particular propagation environment.

Another technique for handover between microcells and macrocells has reportedly been adopted for GSM Phase 2 [40]. To encourage stationary users to enter the microcell there is a permanent positive offset on the received signal level from the microcell. To keep fast-moving users out of the microcells, a user is discouraged from choosing a microcell immediately, via a received signal level offset for a penalty time period. Supercells are designed to provide coverage in rural areas. In an analogous way, a large negative offset is used to keep users out of the supercells whenever possible.

Other related work includes a high-level statement of handover between satellite and terrestrial networks [41]. The scheme involves explicit user registration with the terrestrial network. A handover from a satellite to a terrestrial system is mobile-controlled; a handover from a terrestrial system to a satellite is mobile-assisted. Design issues associated with placing isolated microcells on top of macrocells are discussed in [42]. Various techniques to locate a user can be used in the decision of how many channels to assign to a particular microcell and whether or not to hand a mobile terminal over to a microcell. Paging and location updating procedures may use either or both of the layers; the author's formulation favors microcellular location updating. A high-level cost formulation is presented for both a microcellular and a macrocellular system that includes base station, transmission line, and network costs [43]. Minimizing the total cost yields an optimum cell size that depends on the number of subscribers.

Integrated Systems

This subsection summarizes published work that attempts to cover a geographic area with two dissimilar systems, where one deploys macrocells and the other microcells.

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	Lin *et al.* [56]	Lagrange *et al.* [58]	Chin *et al.* [59]	Hu *et al.* [60]
New attempts:				
in lowest tier	X	X		X
in initial tier			X	
retry in next tier	X			X
Number of tiers	2	2	3	3
Handovers:				
level 1 → level 1	X	X	X	X
level 2 → level 2	X		X	X
level 3 → level 3			X	X
level x → level x + 1	X	X	X	X
level x → level x – 1			X	

■ **Table 2.** *Comparison of modeling assumptions.*

The frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) techniques can be combined in various ways. A system such as GSM is a combined TDMA/FDMA system. The Joint Technical Committee on Wireless Access (JTC) has proposed a system with combined TDMA and CDMA [44].

One major motivation for macrocell/microcell overlays is increased capacity without increased handover rates. A system with CDMA in both the macrocells and microcells using the same radio frequency (RF) spectrum [45] overcomes interference from the higher tier by forcing users in the microcell to transmit at a higher power than that necessary to overcome the propagation loss. The end result is that the cells are not overlaid; the microcell punches a hole in the macrocell. Thus, no reduction in the rate of handover is possible.

The four possible macrocell/microcell overlay schemes were enumerated in [46]:

- CDMA in macrocells with TDMA in microcells
- TDMA in macrocells with CDMA in microcells
- TDMA timeslot sharing between macrocells and microcells
- Orthogonal splitting of frequency channels.

A radio link performance study of these systems showed that, even under optimistic assumptions, the system capacity of the macrocellular and microcellular systems is jointly maximized by the orthogonal sharing approach [46]. This works for both CDMA and TDMA at the cost of a reduction in trunking efficiency. It is better suited to TDMA due to the reduced bandwidth requirement [45].

The capacity of a broadband CDMA (B-CDMA) system overlay of GSM was studied when carefully placed notch filters remove the nine strongest GSM interferences at the B-CDMA base station [47]. A threefold increase in total system capacity is reported. Interestingly enough, a significant capacity increase can be achieved without the filters. These results need to be compared carefully with those reported elsewhere [46]. There are two factors that may have contributed to this difference in results: reducing the TDMA-to-CDMA channel-to-interference ratio (CIR) requirements from 6 dB to 4.5 dB, and allowing the TDMA system to be sectorized.

A qualitative comparison of a CDMA system, a TDMA/FDMA system, and a proposed TDMA/CDMA [48] argues that TDMA/CDMA has higher capacity than TDMA/FDMA only when suitable interference suppression techniques are employed. The intracell TDMA capability permits variable capacity assignment possible in CDMA only via variable spreading gain and multicode techniques [49, 50].

Time-slot alignment between two dissimilar systems is considered [51] as a potential bottleneck for effective intersystem handover for a TDMA orthogonal overlay. The performance of the GSM traffic channel in a GSM-to-Digital European Cordless Telecommunication (DECT) and a GSM-to-wireless access communications system (WACS) handover is considered for both full-rate and half-rate DECT and WACS systems. For DECT a slight modification (shortening) of the frame length would greatly improve interoperability. For WACS, whose radio link was standardized in [9], the 2 ms frame is shown to be preferable to the 2.5 ms variety.

Teletraffic

The teletraffic implications of handover for a cellular system in steady state are modeled using a birth-death process [52]. Key performance metrics include new call blocking, handover failure, forced termination probability, and carried traffic. The model claims to include handover of multiple calls on the same platform (e.g., a bus or train). Although not stated, this methodology may be applicable to the study of GSM multibearer handover, defined in Section 9.1.15 of GSM [53], as well as the multicode and multirate variants of IS-95 CDMA [49, 50].

The performance of a macrocell/microcell system is studied via simulation for three scenarios: macrocells only, macrocells with big microcells, and macrocells with small microcells. Small microcells are deployed on each corner, while big microcells cover several city blocks. The performance metrics are call blocking, handover blocking, call dropping probability, and the mean number of handovers per call. A 1 percent call blocking probability and a 0.2 percent call dropping probability (from [55]) are used in this work. Results also consider the queuing of handover requests. It is suggested that priority for handover should be given to fast-moving mobiles [54].

A microcell/macrocell overlay is studied analytically [56]. New calls try to join the microcells first; if they are blocked, they attempt to access the macrocells. Macrocell users never hand over out of the macrocell layer; blocked microcell handovers attempt to access the macrocell. Given an assumed distribution of the time spent in a microcell, and the assumption of equal treatment for handovers and new call requests, results report the probability that a call is not completed due to being either blocked or not handed over. Also assuming that new calls are allowed to access only the microcells, a Markov modulated Poisson process (MMPP) [57] model of the overflow traffic from the microcell layer to the macrocell layer is developed [58]; simulation verifies the analysis. The call blocking and dropping is derived for the macrocellular layer with the assumption that macrocells are large and macrocellular handovers never occur. Also included are Erlang-B results which understate blocking due to the fact that the overflow process is not Poisson. An overlay slightly increases call blocking but greatly decreases call dropping.

A teletraffic analysis of a three-layer hierarchical system based on Markov chains is used to evaluate call blocking, call dropping, and channel utilization [59]. The three tiers are microcells, macrocells, and satellites. Mobiles can be either single- or dual-mode. Dual-mode mobiles can use both land and satellite networks. Calls are admitted only if they find a channel in their initial tier. Handovers are allowed to try higher tiers if the initial attempt fails; they will return to the lower tier when possible, although not in the particular cell in which the original attempt failed. Numerical examples are given. A similar system is evaluated in which a user tries to access the lowest level first and then is allowed to retry in higher tiers [60]; during handover the call cannot be directed to a lower level. Analytic techniques based on overflow traffic modeling

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are used to evaluate the blocking and forced termination probabilities.

Table 2 compares the modeling work described above. A few crucial differences between the first and second approaches are not included in the table. Unlike the second approach, the first approach allows handovers between macrocells. The first approach allows failed new call attempts in the microcell level to try again in the macrocell level. On the other hand, the second approach accounts for the non-Poisson nature of the handover overflow traffic and compares their results with the Erlang-B results; the first approach relies on Erlang-B. Of special interest is the fact that only the third approach allows users to hand over down to a lower tier.

The performance of a macrocell/microcell system is studied via simulation for three scenarios: macrocells only, macrocells with big microcells, and macrocells with small microcells.

SUMMARY

To meet the growing demand for highly mobile wireless communication services, cellular system providers will continue to deploy additional cell sites and introduce increasingly complex systems, for both the radio link and the network infrastructure. As more users are supported, the ever-growing concerns regarding the limitations of switching and signaling infrastructures have been met by a diverse suite of architectural and algorithmic methods. A prevalent underlying theme is the techniques used to control the handover of users as they move between shrinking cells, at greater speeds, and with stricter requirements on both the QoS delivered to the user and the operational costs associated with a connection. Efforts to quantify the performance of particular approaches have become common within the literature and attempt to answer questions such as:

- Does a user get admitted?
- Does a call get prematurely terminated?
- How many handovers are made, and are they necessary to meet the QoS?
- How far into the coverage area of another cell does a user drift?
- What is the duration of service interruption during a handover?

The decision to initiate a handover depends on a number of control variables. The measurement of received signal strength must be averaged over time to remove the rapid fluctuations due to multipath propagation. Averaging windows vary in their shape and length. Beyond a certain point, where the received signal is too weak or is dangerously close to becoming too weak, a handover is required. A threshold level may provide a trigger to commence a handover. Preventing a user from bouncing back and forth between two base stations is another key issue in handover algorithm design. Two approaches are the hysteresis margin and dwell timer approaches. The former only allows a handover to a base station which is stronger than the current one by at least a fixed or time varying hysteresis margin. The latter restricts the minimum time between two handovers.

Several canonical approaches for a handover criteria combine the elemental control variables. The kernel of each approach is the relative signal strength criterion which induces a handover to a base station whose signal strength is stronger than that of the current base station. This criterion may generate an unnecessary handover when the current base is still strong enough. The relative signal strength with threshold approach allows a handover only if the current base signal strength drops below the threshold level. Immediately after a handover, a rapid change in received signal strengths may force a handover back to the original base station. This "ping-pong" may continue until the mobile moves sufficiently far into the coverage area of a new cell. Instead of a threshold level, relative signal strength with hysteresis allows a handover only if the new base is stronger than the current base by a hysteresis margin. While this approach reduces ping-pongs, it suffers from the initial unnecessary handover problem. An obvious solution is to combine the threshold level with the hysteresis margin to create a strategy called relative signal strength with hysteresis and threshold.

The application of the control variables within the basic canonical approaches has been studied in the literature only for cases involving two or three cells of the same size. From these studies it is possible to gain some fundamental insight into the behavior of the system. The classical performance methods trade the number of ping-pongs against the handover delay. These costs can be viewed as fixed network cost and radio link cost, respectively. Results indicate that either increasing the hysteresis margin, increasing the length of the averaging window, decreasing the threshold level, or increasing the dwell timer will reduce the number of handovers and increase the handover delay. The sensitivity of the results to a particular control variable may depend on the others.

A detailed understanding of the propagation environment is needed to motivate any comprehensive investigation into appropriate choices of these control parameters. While averaging can effectively remove rapid fluctuations due to fast fading, it may delay the handover decision to the point where the user no longer has a satisfactory channel. Under LOS conditions, averaging is a valuable tool to avoid ping-pong handovers that result from an initial premature decision. For non-LOS conditions which occur when a user turns a corner, averaging is totally ineffective. In this case, a little averaging combined with a hysteresis margin is needed to detect the sudden drop in signal strength. Thus, different propagation environments may require considerably different settings of the control variables to achieve the same performance requirements.

Combining macrocells and microcells further complicates the control of a handover. One study proposed combining two trigger mechanisms, one to work when the user is in the microcellular plane, the other when the user is in the macrocellular plane. The combined approach allows the handover decision to be made without knowledge of the plane within which the user is communicating. The first trigger combines a small hysteresis margin with long averaging, and the second trigger combines a large hysteresis margin with a short averaging interval. The first trigger is tuned for the macrocellular plane, the second for the microcellular plane. Another combined macro-/microcell control scheme considers using hysteresis offsets to favor a particular plane. A permanent positive offset favors handover to the microcellular plane for traffic reasons. A time-varying negative offset delays entry into the microcell plane until a user is present for a particular time interval. This prevents passing a fast user to the lower plane and causing excessive handovers as well as risking drop-

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ping the call. This scheme is supported within GSM Phase 2.

Velocity-based assignment techniques are predicated on the intuitive assumption that fast users should be placed in macrocells and slow users in macrocells. Microcells are needed to increase system capacity. An umbrella layer of macrocells reduces the handover rate as users cross quickly through the system coverage area. It is postulated that velocity-based assignment achieves the goals of high capacity and low handover rate. Before the system can determine the speed of the user, it may need to assign it a radio channel to support its call setup request. Various authors have assumed the call begins in the microcellular plane; others have assumed the call should begin in the macrocellular plane; many have assumed macrocell-to-microcell handovers are not permitted.

As more users are supported, the ever-growing concerns regarding the limitations of switching and signaling infrastructures have been met by a diverse suite of architectural and algorithmic methods.

Heterogeneous multitiered systems include overlaying CDMA and TDMA systems using the same or different spectrum in the macro/microcell arrangement. Overlaying a broadband CDMA system over a TDMA system or a TDMA system over a CDMA system are possible options. A CDMA-over-CDMA system using the same spectrum is not possible due to the fact that the microcells "punch holes" in the coverage area of the macrocells; thus, a single-tier system results. Orthogonal overlays seem to work well, but orthogonal CDMA-over-CDMA overlays require considerable spectrum. TDMA-over-TDMA overlays have time slot and frame alignment problems that limit the ability of the mobile to scan all time slots on the other tier's channel. Disjoint adjacent systems pose further challenges due to the limitations of the radio technology within the mobile terminal. Reported work on the teletraffic implications of a macro-/microcell overlay is largely theoretical.

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References

[1] M. Gudmundson, "Analysis of Handover Algorithms," *Proc. Vehicular Tech. Conf. '91*, St. Louis, MO, May 19–22, 1991, pp. 537–42.

[2] M. E. Anagnostou and G. C. Manos, "Handover Related Performance of Mobile Communication Networks," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 111–14.

[3] G. P. Pollini, "A Catalog of Handover Algorithms for the Cellular Packet Switch," WINLAB Tech. Rep. TR-48, Rutgers, Jan. 1993.

[4] V. Kapoor, G. Edwards, and R. Sankar, "Handoff Criteria for Personal Communication Networks," *Proc. ICC '94*, New Orleans, LA, May 1–5, 1994, pp. 1297–1301.

[5] C-N. Chuah, R. D. Yates, and D. J. Goodman, "Integrated Dynamic Radio Resource Management," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 584–88.

[6] C-N. Chuah and R. D. Yates, "Evaluation of a Minimum Power Handoff Algorithm," *Proc. IEEE Int'l. Symp. on Personal, Indoor, and Mobile Radio Commun. (PIMRC) '95*, Toronto, Canada, Sept. 27–29, 1995, pp. 814–18.

[7] K. G. Chen, "Integrated Dynamic Radio Resource Management of Wireless Communication Systems," M.S. thesis, Rutgers, May 1996.

[8] GSM 05.08 (prETS 300 578) "European Digital Cellular Telecommunications System (Phase 2); Radio Subsystem Link Control," 3rd ed., May 1995.

[9] JTC(AIR)95.06.08-033R3, "Baseline Text for TAG 3 (PACS)," Section 6.2, June 8, 1995.

[10] M. Asawa and W. E. Stark, "A Framework for Optimal Scheduling of Handoffs in Wireless Networks," *Proc. Globecom '94*, San Francisco, CA, Nov. 28– Dec. 2, 1994, pp. 1669–73.

[11] J. P. Castro, "Handoff Techniques in Universal Mobile Communications," *Proc. IEEE Int'l. Conf. Universal Personal Commun. (ICUPC) '93*, Ottawa, Canada, Oct. 12–15, 1993, pp. 844–48.

[12] A. Bottcher and M. Werber, "Strategies for Handover Control in Low Earth Orbit Satellite Systems," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 1616–20.

[13] R. Vijayan and J. M. Holtzman, "The Dynamic Behavior of Handoff Algorithms," *Proc. 1st ICUPC '92*, Dallas, TX, paper 2.03, Sept. 29–Oct. 2, 1992.

[14] R. Vijayan and J. M. Holtzman, "Analysis of Handover Algorithms Using Nonstationary Signal Strength Measurements," *Proc. Globecom '92*, Orlando, FL, paper 41.2, Dec. 6–9, 1992.

[15] G. E. Corazza, D. Giancristofaro, and F. Santucci, "Characterization of Handover Initialization in Cellular Mobile Radio Networks," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 1869-72.

[16] N. Zhang and J. M. Holtzman, "Analysis of Handoff Algorithms Using Both Absolute and Relative Measurements," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 82–86.

[17] N. Zhang and J. M. Holtzman, "Analysis of a CDMA Soft Handoff Algorithm," *Proc. PIMRC '95*, Toronto, Canada, Sept. 27–29, 1995, pp. 819–23.

[18] G. N. Senarath and D. Everitt, "Performance of Handover Priority and Queuing Systems under Different Handover Request Strategies for Microcellular Mobile Communication Systems," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 897–901.

[19] D. Munoz-Rodriquez *et al.*, "Neural Supported Hand Off Methodology in Micro Cellular Systems," *Proc. Vehicular Tech. Conf. '92*, Denver, CO, May 10–13, 1992, pp. 431–34.

[20] H. Maturino-Lozoya, D. Munoz-Rodriguez, and H. Tawfik, "Pattern Recognition Techniques in Handoff and Service Area Determination," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 96–100.

[21] G. Liodakis and P. Stravroulakis, "A Novel Approach in Handover Initiation for Microcellular Systems," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 1820–23.

[22] O. E. Kelly, and V. V. Veeravalli, "A Locally Optimal Handoff Algorithm," *Proc. IEEE PIMRC '95*, Toronto, Canada, Sept. 27–29, 1995, pp. 809–13.

[23] O. Grimlund and B. Gudmundson, "Handoff Strategies in Microcellular Systems," *Proc. Vehicular Tech. Conf. '91*, St. Louis, MO, May 19–22, 1991, pp. 505–10.

[24] P-E. Ostling, "Implications of Cell Planning on Handoff Performance in Manhattan Environments," *Proc. PIMRC '94*, The Hague, The Netherlands, paper 6.1, Sept. 18–22, 1994.

[25] S. T. S. Chia, "The Control of Handover Initiation in Microcells," *Proc. Vehicular Tech. Conf. '91*, St. Louis, MO, May 19–22, 1991, pp. 531–36.

[26] P-E. Ostling, "Handover with Simulcasting," *Proc. Vehicular Tech. Conf. '92*, Denver, CO, May 10–13, 1992, pp. 823–26.

[27] S. Zurbes, W. Papen, and W. Schmidt, "A New Architecture for Mobile Radio with Macroscopic Diversity and Overlapping Cells," *Proc. IEEE PIMRC '94*, The Hague, The Netherlands, paper 6.4, Sept. 18–22, 1994.

[28] H. Asakura and T. Fujii, "Combining Micro and Macro Cells in a Cellular System," *Proc. IEEE ICUPC '93*, Ottawa, Canada, Oct. 12–15, 1993, pp. 728–31.

[29] J. Zander, "Generalized Reuse Partitioning in Cellular Mobile Radio," *Proc. Vehicular Tech. Conf. '93*, Secaucus, NJ, May 18–20, 1993, pp. 181–84.

[30] H. Furukawa, and Y. Akaiwa, "A Microcell Overlaid with Umbrella Cell System," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 1455–59.

[31] J. Naslund *et al.*, "An Evolution of GSM," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 348–52.

[32] K. Ivanov, and G. Spring, "Mobile Speed Sensitive Handover in a Mixed Cell Environment," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 892–96.

[33] M. Benveniste, "Cell Selection in Two-Tier Microcellular/Macrocellular Systems," *Proc. Globecom '95*, Singapore, Nov. 1995.

[34] K. Kawabata, T. Nakamura, and E. Fukuda, "Estimating Velocity Using Diversity Reception," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 371–74.

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Combining macrocells and microcells further complicates the control of a handover. One study proposed combining two trigger mechanisms, one to work when the user is in the microcellular plane, the other when the user is in the macrocellular plane.

[35] M. D. Austin and G. L. Stuber, "Velocity Adaptive Handover Algorithms for Microcellular Systems," *Proc. IEEE ICUPC '93*, Ottawa, Canada, Oct. 12–15, 1993, pp. 793–97.

[36] M. D. Austin and G. L. Stuber, "Directed Biased Handoff Algorithms for Urban Microcells," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 101–5.

[37] R. Rezaiifar, A. M. Makowski, and S. Kumar, "Optimal Control of Handoffs in Wireless Networks," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 887–91.

[38] C. W. Sung and W. S. Wong, "User Speed Estimation and Dynamic Channel Allocation in Hierarchical Cellular System," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 91–95.

[39] A. Murase, I. C. Symington, and E. Green, "Handover Criterion for Macro and Microcellular Systems," *Proc. Vehicular Tech. Conf. '91*, St. Louis, MO, May 19–22, 1991, pp. 524–30.

[40] P. A. Ramsdale and W. B. Harrold, "Techniques for Cellular Networks Incorporating Microcells," *Proc. IEEE PIMRC '92*, Boston, MA, Oct. 19–21, 1992, pp. 169–73.

[41] H. K. Lau, P. C. K. Liu, and K. C. Li, "Hand-Off Analysis for an Integrated Satellite and Terrestrial Mobile Switch over a Fading Channel," *Proc. IEEE PIMRC '92*, Boston, MA, Oct. 19–21, 1992, pp. 397–401.

[42] M. Murata and E. Nakano, "Enhancing the Performance of Mobile Communications Systems," *Proc. IEEE ICUPC '93*, Ottawa, Canada, Oct. 12–15, 1993, pp. 732–36.

[43] K. Ogawa, T. Hattori, and H. Yoshida, "Optimum Multi-Layered Cell Architecture for Personal Communications Systems with High Degree of Mobility," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 644–48.

[44] PCS 2000, "A Composite CDMA/TDMA Air Interface Compatibility Standard for Personal Communications in 1.8-2.2 GHz for Licensed and Unlicensed Applications," ver. 1, TR46.3/PN-3390, T1P1/94-089, Dec. 1994.

[45] H. Eriksson *et al.*, "Multiple Access Options for Cellular Based Personal Communications," *Proc. Vehicular Tech. Conf. '93*, Secaucus, NJ, May 18–20, 1993, pp. 957–62.

[46] C-L. I, L. J. Greenstein, and R. D. Gitlin, "A Microcell/Macrocell Cellular Architecture for Low- and High-Mobility Wireless Users," *Proc. Globecom '91*, Phoenix, AZ, Dec. 2–5, 1991, pp. 1006–11; in *IEEE Trans. Vehicular Tech.*, vol. VT-11, Aug. 1993, pp. 88591.

[47] D. M. Grieco and D. L. Schilling, "The Capacity of Broadband CDMA Overlaying a GSM Cellular System," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 31–35.

[48] M. L. Honig, and U. Madhow, "Hybrid Intra-Cell TDMA/Inter-Cell CDMA with Inter-Cell Interference Suppression for Wireless Networks," *Proc. Vehicular Tech. Conf. '93*, Secaucus, NJ, May 18–20, 1993, pp. 309–12.

[49] C-L. I *et al.*, "Performance of Multi-Code CDMA Wireless Personal Communications Networks," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 907–11.

[50] C-L. I and K. K. Sabnani, "Variable Spreading Gain CDMA with Adaptive Control for Integrated Traffic in Wireless Networks," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995.

[51] N. W. Whinnett, "Handoff Between Dissimilar Systems: General Approaches and Air Interface Issues for TDMA Systems," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 953–57.

[52] S. Rappaport, "Modeling the Hand-Off Problem in Personal Communications Networks," *Proc. Vehicular Tech. Conf. '91*, St. Louis, MO, May 19–22, 1991, pp. 517–23.

[53] GSM 04.08 (prETS 300 557) "European Digital Cellular Telecommunications System (Phase 2); Mobile Radio Interface Layer 3 Specification," 2nd ed., May 1995.

[54] G. L. Lyberopoulos, J. G. Markoulidakis, and M. E. Anagnostou, "The Impact of Evolutionary Cell Architectures on Handover in Future Mobile Telecommunication Systems," *Proc. Vehicular Tech. Conf. '94*, Stockholm, Sweden, June 8–10, 1994, pp. 120–24.

[55] RACE Industrial Consortium, Common Functional Specification D730, "Mobile Network Subsystems," issue B, Dec. 1991.

[56] Y-B. Lin, L-F. Chang, and A. Noerpel, "Modeling Hierarchical Microcell/Macrocell PCS Architecture," *Proc. ICC '95*, Seattle, WA, June 18–22, 1995; submitted to *ACM/IEEE Trans. on Networking*, pp. 405–9.

[57] W. Fischer and K. S. Meier-Hellstern, "The MMPP Cookbook," *Performance Evaluation*, vol. 18, 1992, pp. 149–71.

[58] X. Lagrange and P. Godlewski, "Teletraffic Analysis of Hierarchical Cellular Networks," *Proc. Vehicular Tech. Conf. '95*, Chicago, IL, July 25–28, 1995, pp. 882–86.

[59] L-P. Chin, and J-F. Chang, "Performance Analysis of a Hierarchical Cellular Mobile Communication System," *Proc. IEEE ICUPC '93*, Ottawa, Canada, Oct. 12–15, 1993, pp. 128–32.

[60] L-R. Hu and S. S. Rappaport, "Personal Communications Systems Using Multiple Hierarchical Cellular Overlays," *Proc. IEEE ICUPC '94*, San Diego, CA, Sept. 27–Oct. 1, 1994, pp. 397–401.

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