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Abstract

Handoff is an essential element of cellular communications. Efficient handoff algorithms are a cost-effective way of enhancing the capacity and QoS of cellular systems. This article presents different aspects of handoff and discusses handoff related features of cellular systems. Several system deployment scenarios that dictate specific handoff requirements are illustrated. An account of handoff-related resource management tasks of cellular systems is given. Implementation of the handoff process is explained. Several mechanisms for evaluation of handoff-related system performance are described.

Handoff in Cellular Systems

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Handoff is a process of transferring a mobile station (MS) from one base station (BS) or channel to another. The channel change due to handoff may be through a time slot, frequency band, codeword, or combination of these for time-division multiple access (TDMA), frequency-division multiple access (FDMA), code-division multiple access (CDMA), or a hybrid scheme, respectively [1].

This article includes four major topics.

Topic 1: Deployment Scenarios and Handoff — Topic 1 describes different system deployment scenarios and their constraints on the handoff procedure. Handoff algorithms with a specific set of parameters cannot perform uniformly well in different communication system deployment scenarios since these scenarios are characterized by specific environments. Examples of different system structures include macrocells, microcells, overlays, integrated cellular systems, integrated cordless and cellular systems, and integrated terrestrial and satellite systems. Note that these system structures are expected to coexist in future wireless communication systems and warrant closer study.

Topic 2: Resource Management in Cellular Systems — Topic 2 views handoff and other resource management tasks and details handoff-related system performance improvement. Prioritizing handoff is one way to improve handoff-related system performance. Several handoff prioritization schemes (e.g., guard channels and queuing) are discussed. *Handoff* represents one of the radio resource management tasks carried out by cellular systems. Some other resource management functions include *admission control*, *channel assignment*, and *power control*. If some of the resource management tasks are treated in an integral manner, better overall performance can be obtained in a global sense by making appropriate trade-offs.

Topic 3: Implementation of Handoff — Topic 3 describes how handoff procedure is implemented. The decision making process of handoff may be centralized or decentralized (i.e., the handoff decision may be made at the MS, BS, or mobile switching center, MSC). Different systems use different approaches to execute the process of handoff, and handoff protocols characterize these approaches.

Topic 4: Analysis of Handoff Algorithms — Three basic mechanisms have been used to evaluate the performance of handoff algorithms, and these mechanisms — the analytical approach, simulation approach, and emulation approach — are described in topic 4.

Cellular System Deployment Scenarios

The radio propagation environment and related handoff challenges are different in different cellular structures. A handoff algorithm with fixed parameters cannot perform well in different system environments. Specific characteristics of the communication systems should be taken into account while designing handoff algorithms. Several basic cellular structures (e.g., macrocells, microcells, and overlay systems) and special architectures (e.g., underlays, multichannel bandwidth systems, and evolutionary architectures) are described next. Integrated cordless and cellular systems, integrated cellular systems, and integrated terrestrial and satellite systems are also described.

Macrocells

Macrocell radii are in several kilometers. Due to the low cell-crossing rate, centralized handoff is possible despite the large number of MSs the MSC has to manage. The signal quality in the uplink and downlink is approximately the same. The transition region between the BSs is large; handoff schemes should allow some delay to avoid flip-flopping. However, the delay should be short enough to preserve the signal quality because the interference increases as the MS penetrates the new cell. This cell penetration is called *cell dragging*. Macrocells have relatively gentle path loss characteristics [2]. The averaging interval (i.e., the time period used to average the signal strength variations) should be long enough to get rid of fading fluctuations. First- and second-generation cellular systems provide wide-area coverage even in cities using macrocells [3]. Typically, a BS transceiver in a macrocell transmits high output power with the antenna mounted several meters high on a

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This work was sponsored by the MPRG Industry Affiliates Program at Virginia Tech.

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tower to illuminate a large area. Figure 1 shows three clusters of seven cells in a macrocellular system. A cluster consists of a group of cells marked A through G.

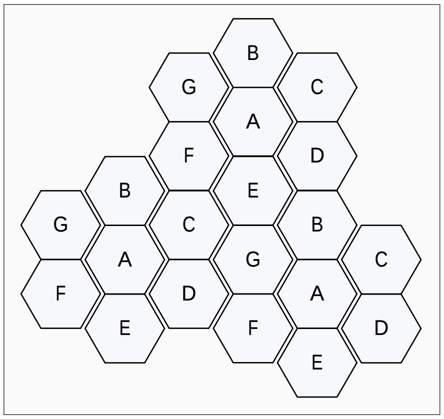


Figure 1. *Seven-cell clusters in a macrocellular system.*

Microcells

Some capacity improvement techniques (e.g., larger bandwidths, improved methods for speech coding, channel coding, and modulation) will not be sufficient to satisfy the required service demand. The use of microcells is considered the single most effective means of increasing the capacity of cellular systems [3]. Microcells increase capacity, but radio resource management becomes more difficult. Microcells can be classified as one-, two-, or three-dimensional, depending on whether they are along a road or a highway, covering an area such as a number of adjacent roads, or located in multilevel buildings, respectively [4]. Microcells can be classified as hot spots (service areas with a higher traffic density or areas that are covered poorly), downtown clustered microcells (contiguous areas serving pedestrians and mobiles), and in-building 3-D cells (serving office buildings and pedestrians) [5].

Typically, a BS transceiver in a microcell transmits low output power with the antenna mounted at lamppost level (approximately 5 m above ground) [3]. The MS also transmits low power, which leads to longer battery life. Since BS antennas have lower heights compared to the surrounding buildings, RF signals propagate mostly along the streets [6–8]. The antenna may cover 100–200 m in each street direction, serving a few city blocks. This propagation environment has low time dispersion, which allows high data rates [9].

Microcells are more sensitive to the traffic and interference than macrocells due to short-term variations (e.g., traffic and interference variations), medium/long-term alterations (e.g., new buildings), and incremental growth of the radio network (e.g., new BSs) [10]. The number of handoffs per cell is increased by an order of magnitude, and the time available to make a handoff is decreased [11]. Using an umbrella cell is one way to reduce the handoff rate. Due to the increase in the microcell boundary crossings and expected high traffic loads, a higher degree of decentralization of the handoff process becomes necessary [1].

Microcells encounter a propagation phenomenon called the *corner effect*. The corner effect is characterized by a sudden large drop (e.g., 20–30 dB) in signal strength (e.g., at 10–20 m distance) when a mobile turns around a corner. The corner effect is due to the loss of the line of sight (LOS) component from the serving BS to the MS. The corner effect demands a faster handoff and can change the signal quality very fast. The corner effect is hard to predict. A long measurement averaging interval is not desirable due to the corner effect. Moving obstacles can temporarily hinder the path between a BS and an MS, which resembles the corner effect.

In a microcellular system there may be two types of handoff scenarios: an LOS handoff and a non-LOS (NLOS) handoff. An LOS handoff is a handoff from one LOS BS to another LOS BS. An NLOS handoff is a handoff from an NLOS BS to an LOS BS. In an LOS handoff, premature handoff requests should be prevented. In an NLOS handoff, the handoff must be done as fast as possible as the user turns the corner. Some of the solutions to deal with these different requirements for LOS and NLOS handoffs in microcells are umbrella cells, macrodiversity, and switching to mobile-controlled handoff [2].

Reference [12] studies the properties of symmetrical cell plans in a Manhattan-type environment. Cell plans affect signal-to-interference ratio (SIR) performance in the uplink and downlink significantly. Symmetrical cell plans have four nearest co-channel BSs located at the same distance. Such cell plans can be classified into *half-square* (HS), *full-square* (FS), and *rectangular* (R) cell plans. These cell plans are described next.

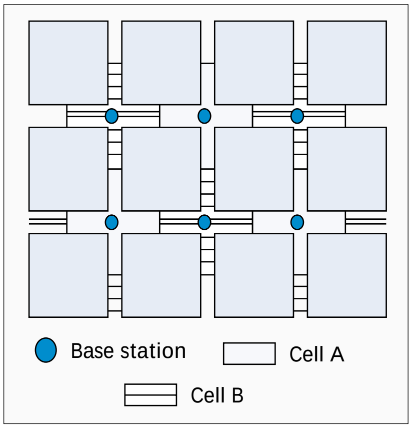


Figure 2. *A half-square cell plan in a microcellular system.*

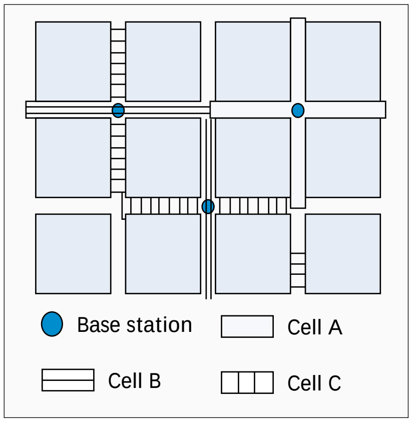


Figure 3. *A full-square cell plan in a microcellular system.*

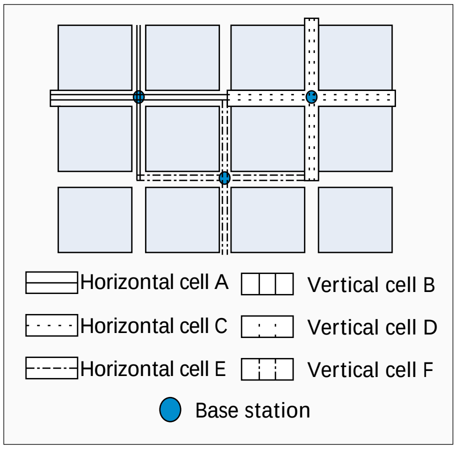
Half-Square Cell Plan — This cell plan places BSs with omnidirectional antennas at each intersection, and each BS covers half a block in all four directions. This cell plan avoids the street corner effect and provides the highest capacity. This cell plan has only LOS handoffs. Figure 2 shows an example of a half-square cell plan in a microcellular system.

Full-Square Cell Plan — There is a BS with an omnidirectional antenna located at every other intersection, and each BS covers a block in all four directions. It is possible for an MS to experience the street corner effect for this cell plan. The FS cell plan can have LOS or NLOS handoffs. Figure 3 shows an example of a full-square cell plan in a microcellular system.

Rectangular Cell Plan — Each BS covers a fraction of either a horizontal or vertical street with the BS located in the middle of the cell. This cell plan can easily be adapted to market penetration. Fewer BSs with high transmit power can be used initially. As user density increases, new BSs can be added with reduced transmit power from appropriate BSs. The street corner effect is possible for this cell plan. The R cell plan can have LOS or NLOS handoffs. Figure 4 shows an example of a rectangular cell plan in a microcellular system.

Macrocell/Microcell Overlays

Congestion of certain microcells, the lack of service of microcells in some areas, and high speed of some users are some reasons for higher handoff rates and signaling load for microcells [13]. To alleviate some of these problems, a mixed-cell architecture (called an *overlay/underlay system*) consisting of large-size macrocells (called *umbrella cells* or *overlay cells*) and small-size microcells (called *underlay cells*) can be used. Figure 5 illustrates an overlay system.



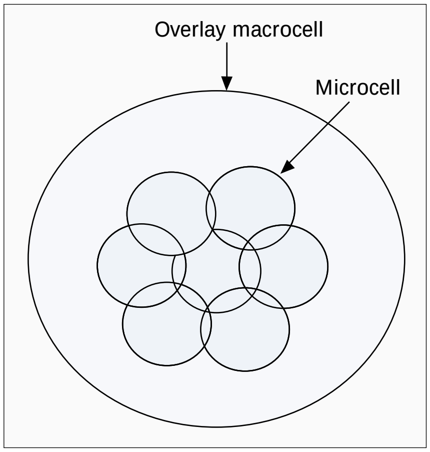
■ **Figure 4.** *A rectangular cell plan in a microcellular system.*

The macrocell/microcell overlay architecture provides a balance between maximizing the number of users per unit area and minimizing the network control load associated with handoff. Macrocells provide wide-area coverage beyond microcell service areas and ensure better intercell handoff [14]. Microcells provide capacity due to greater frequency reuse and cover areas with high traffic density (called *hot spots*). Examples of hot spots include an airport, a railway station, or a parking lot. In less congested areas (e.g., areas beyond a city center or outside the main streets of a city) traffic demand is not very high, and macrocells can provide adequate coverage in such areas. Macrocells also serve high-speed MSs and the areas not covered by microcells (e.g., due to lack of channels or the MS being out of the microcell range). Also, after the microcellular system is used to its fullest extent, the overflow traffic can be routed to macrocells. One of the important issues for the overlay/underlay system is the determination of optimum distribution of channels in the macrocells and microcells [15]. Reference [16] evaluates four approaches to sharing the available spectrum between the two tiers. Approach 1 uses TDMA for microcell and CDMA for macrocell. Approach 2 uses CDMA for microcell and TDMA for macrocell. Approach 3 uses TDMA in both tiers, while approach 4 uses orthogonal frequency channels in both tiers.

The overlay/underlay system has several advantages over a pure microcell system [17]:

- The BSs are required only in high traffic load areas. Since it is not necessary to cover the whole service area with microcells, infrastructure costs are saved.
- The number of handoffs in an overlay system is much less than in a microcell system because fast-moving vehicles can be connected to the overlay macrocell.
- Both calling from an MS and location registration can easily be done through the microcell system.

There are several classes of umbrella cells [17]. In one class, orthogonal channels are distributed between microcells and macrocells. In another class, microcells use channels that are temporarily unused by macrocells [18]. In yet another class, microcells reuse the channels already assigned to macrocells and use slightly higher transmit power levels to counteract the interference from the macrocells. Within the overlay/underlay system environment, four types of handovers need to be managed [19]: microcell to microcell, microcell to macrocell, macrocell to macrocell, and macrocell to microcell.



■ **Figure 5.** *A microcell/macrocell overlay system.*

Reference [20] describes combined cell splitting and overlaying. Reuse of channels in the two cells is done by establishing an overlaid small cell served by the same cell site as the large cell. Small cells reuse the split cell's channels because of the large distance between the split cell and the small inner cell, while the large cell cannot reuse these channels. Overlaid cells are approximately 50 percent more spectrally efficient than *segmenting* (the process of distributing the channels among the small- and large-size cells to avoid interference).

A practical approach for implementation of a microcell system overlaid with an existing macrocell system is proposed in [17]. This reference introduces channel segregation (a self-organized dynamic channel assignment) and automatic transmit power control to obviate the need to design channel assignment and transmit power control for the microcell system. The available channels are reused automatically between microcells and macrocells. A slight increase of transmit power for the microcell system compensates for the macrocell-to-microcell interference. Simulation results indicate that the local traffic is accommodated by the microcells laid under macrocells without any significant channel management effort.

The methodology of the Global System for Mobile Communications (GSM)-based system is extended to the macrocell/microcell overlay system in [21]. The use of random frequency hopping and adaptive frequency planning is recommended, and different issues related to handoff and frequency planning for an overlay system are discussed.

Four strategies are designed to determine a suitable cell for a user for an overlay system [22]. Two strategies are based on the dwell time (the time for which a call can be maintained in a cell without handoff), and the other two strategies are based on user speed estimation. A speed estimation technique based on dwell times is also proposed.

A CDMA cellular system can provide full connectivity between the microcells and the overlaying macrocells without capacity degradation. Reference [5] analyzes several factors that determine the cell size, the soft handoff (SHO) zone, and the capacity of the cell clusters. Several techniques for overlay-underlay cell clustering are also outlined. Application of CDMA to microcell/macrocell overlay have the following major advantages [5]:

- A heterogeneous environment can be illuminated uniformly by using a distributed antenna (with a series of radiators with different propagation delays) while still maintaining a high-quality signal.
- SHO obviates the need for complex frequency planning.

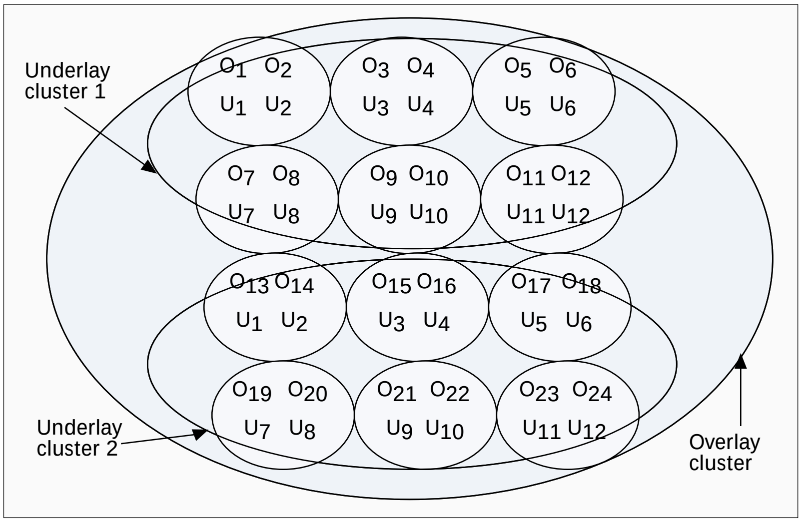
Reference [23] studies the feasibility of a CDMA overlay that can share the 1850–1990 MHz personal communications services (PCS) band with existing microwave signals (transmitted by utility companies and state agencies). The results of several field tests demonstrate the application of such an overlay for the PCS band.

The issue of use of a CDMA microcell underlay for an existing analog macrocell is the focus of [24]. It is shown that high capacity can be achieved in a microcell at the expense of a slight degradation in macrocell performance. Reference [24] finds that transmit and receive notch filters should be used at the microcell BSs. It shows that key parameters for such an overlay are the powers of the CDMA BS and MS transmitters relative to the macrocell BSs and the MSs served by the macrocells.

Reference [25] studies spectrum management in an overlay system. A new cell selection method is proposed, which uses the history of microcell sojourn times. A procedure to determine an optimum velocity threshold for the proposed method is also outlined. A systematic approach to optimal frequency spectrum management is described.

Special Architectures

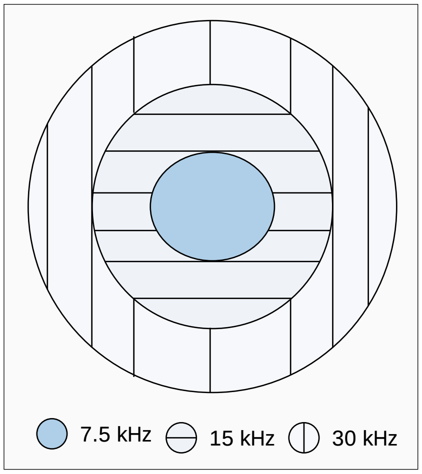
There are several special cellular architectures that try to improve spectral efficiency without a large increase in infrastructure costs. Some of these structures, discussed here, include an underlay/overlay system (which is different from the overlay/underlay system described earlier) and a multichannel bandwidth system. Many cellular systems are expected to evolve from a macrocellular system to an overlay/underlay system. A study that focuses on such evolution is described in [26].



■ **Figure 6.** *An underlay/overlay system.*

Underlay/Overlay System — An underlay/overlay system is different from the overlay/underlay system described earlier. In an overlay/underlay system, frequency spectrum is divided between the macrocells and microcells in such a way that a macrocell uses certain channels throughout the cellular system [27]. Also, the macrocell typically has a separate BS and a transmission tower. However, in an underlay/overlay system, a tighter reuse factor is used within an overlay.

For example, assume that there are 36 channels in a cluster of 12 cells. If there is no overlay or underlay, three channels will be available for each cell. In the conventional overlay/underlay system, two channels per cell can be used in a cluster of 12 microcells, while the macrocell will use the remaining 12 channels throughout the cluster region. If uniform distribution of traffic is assumed, the effective number of channels per cell will still be three (two channels from a microcell and one from a macrocell). On the other hand, in one arrangement of an underlay/overlay scheme, two reuse factors, 12 and 6, will be used instead of just one reuse factor 12, as shown in Fig. 6. Within a cluster of 12 cells, two channels per cell will be used in an overlay system (channels O_1 through O_{24} in Fig. 6), and the remaining 12 channels will be distributed using the reuse factor of six (channels U_1 through U_{12} in Fig. 6). Thus, within a single overlay cluster there will be two underlay clusters, and each underlay cluster has a reuse factor of 6. Hence, effectively there will be four channels per cell in an underlay/overlay system compared to three channels per cell for a non-underlay/overlay system. Further improvement in capacity can be obtained by using an even tighter reuse factor of 3 in an underlay cluster. In this case, there will be four underlay clusters within an overlay cluster. The overlay cluster uses two channels per cell, and the underlay cluster uses four channels per cell. Thus, effectively six channels per cell will be available. The underlay/overlay scheme can enhance capacity of the system without the infrastructure costs because the same BSs, transmission towers, and other hardware can be shared.



■ **Figure 7.** *A multiple-channel-bandwidth system.*

A Multiple-Channel-Bandwidth System — Multiple channel bandwidths can be used within a cell to improve spectral efficiency. In a multiple-channel-bandwidth system (MCBS), a cell has two or three ring-shaped regions with different bandwidth channels [28]. Figure 7 shows an MCBS.

Assume that 30 kHz is the normal bandwidth for a signal. Now, for a three-ring MCBS, 30 kHz channels can be used in the outermost ring, 15 kHz channels in the middle ring, and 7.5 kHz channels in the innermost ring. The areas of these rings can be determined based on the expected traffic conditions. Thus, instead of using 30 kHz channels throughout the cell, different bandwidth channels (e.g., 15 kHz and 7.5 kHz) can be used to increase the number of channels in a cell. The MCBS uses the fact that a wide-bandwidth channel requires a lower carrier-to-interference ratio (C/I) than a narrow-bandwidth channel for the same voice quality. For example, C/I requirements for 30 kHz, 15 kHz, and 7.5 kHz channel bandwidths are 18 dB, 24 dB, and 30 dB, respectively, based on subjective voice quality tests [28]. If the transmit power at a cell cite is the same for all the bandwidths, a wide channel can serve a large cell while a narrow channel can serve a relatively small cell. Moreover, since a wide channel can tolerate a higher level of co-channel interference (CCI), it can afford a smaller D/R ratio (the ratio of co-channel distance to cell radius). Thus, in the MCBS more channels become available due to multiple-bandwidth signals, and frequency can be reused more closely in a given service region due to different C/I requirements.

Integrated Wireless Systems

Integrated wireless systems are exemplified by integrated cordless and cellular systems, integrated cellular systems, and integrated terrestrial and satellite systems. Such integrated systems combine the features of individual wireless systems to achieve the goals of improved mobility and low cost.

Integrated Terrestrial Systems — Terrestrial intersystem handoff may be between two cellular systems or between a cellular system and a cordless telephone system. Examples of systems that need intersystem handoffs include GSM–Digital European Cordless Telephone (DECT), CDMA in macrocells, and TDMA in microcells.

When a call initiated in a cellular system controlled by an MSC enters a system controlled by another MSC, intersystem handoff is required to continue the call [29]. In this case one MSC makes a handoff request to another MSC to save the call. The MSCs need to have software for intersystem handoff if intersystem handoff is to be implemented. Compatibility between the concerned MSCs needs to be considered, too.

There are several possible outcomes of an intersystem handoff [29]:

- A long-distance call becomes a local call when an MS becomes a roamer.
- A long-distance call becomes a local call when a roamer becomes a home mobile unit.
- A local call becomes a long distance call when a home mobile unit becomes a roamer.
- A local call becomes a long-distance call when a roamer becomes a home mobile unit.

There is a growing trend toward service portability across dissimilar systems such as GSM and DECT [30]. For example, it is nice to have intersystem handoff between cordless and cellular coverage. Cost-effective handoff algorithms for such scenarios represent a significant research area. This article outlines different approaches to achieving intersystem handoff. Simulation results are presented for handoff between GSM and DECT/Wide Access Communications System (WACS). The paper shows that a minor adjustment to the DECT specification can greatly simplify the implementation of an MS capable of intersystem handoff between GSM and DECT.

Integrated Terrestrial and Satellite Systems — In an integrated cellular/satellite system, the advantages of satellites and cellular systems can be combined. Satellites can provide wide-area coverage, completion of coverage, immediate service, and additional capacity (by handling overflow traffic). A cellular system can provide a high-capacity economical system. Some of the issues involved in an integrated system are discussed in [31]. In particular, the procedures of GSM are examined for their application to the integrated systems.

The future public land mobile telecommunication system (FPLMTS) will provide a personal telephone system that enables a person with a handheld terminal to reach anywhere in the world [32]. The FPLMTS will include low Earth orbit (LEO) or geostationary Earth orbit (GEO) satellites as well as terrestrial cellular systems. When an MS is inside the coverage area of a terrestrial cellular system, the BS will act as a relay station and provide a link between the MS and the satellite. When an MS is outside the terrestrial system coverage area, it will have a direct communication link with the satellite. Different issues such as system architecture, call handling, performance analysis of the access, and transmission protocols are discussed in [32]. The two handoff scenarios in an integrated system are described below.

Handoff from the Land Mobile Satellite System to the Terrestrial System — While operating, the MS monitors the satellite link and evaluates the link performance. The received signal strengths (RSSs) are averaged (e.g., over a 30 s time period) to minimize signal strength variations. If the RSS falls below a certain threshold N consecutive times (e.g., $N = 3$), the MS begins measuring RSS from the terrestrial cellular system. If the terrestrial signals are strong enough, handoff is made to the terrestrial system, provided that the terrestrial system can serve the MS.

Handoff from the Terrestrial System to the Land Mobile Satellite System — When an MS is getting service from the terrestrial system, the BS sends an acknowledge request (called *page*) at predefined intervals to ensure that the MS is still inside the coverage area. If an acknowledge request signal from the MS (called *page response*) is not received at the BS for N consecutive times, it is handed off to the land mobile satellite system (LMSS).

Reference [33] focuses on personal communication systems with hierarchical overlays that incorporate terrestrial and satellite systems. The lowest level in the hierarchy is formed by microcells. Macrocells overlay microcells and form the middle level in the hierarchy. Satellite beams overlay macrocells and constitute the topmost hierarchy level. Two types of subscribers are considered, satellite-only and dual cellular/satellite. Call attempts from satellite-only subscribers are served by satellite systems, while call attempts from dual subscribers are first directed to the serving terrestrial systems with the satellites taking care of the overflow traffic. An analytical model for teletraffic performance is developed, and performance measures such as traffic distribution, blocking probability, and forced termination probability are evaluated for low-speed and high-speed users.

Handoff Prioritization

One of the ways to reduce the handoff failure rate is to prioritize handoff. Handoff algorithms that try to minimize the number of handoffs give poor performance in heavy traffic situations [34]. In such situations, a significant handoff performance improvement can be obtained by prioritizing handoff.

Introduction to Handoff Priority

Channel assignment strategies with handoff prioritization have been proposed to reduce the probability of forced termination [35, 36]. Two basic methods of handoff prioritization, guard channels and queuing, are explained next.

Guard Channels — Guard channels improve the probability of successful handoffs by reserving a fixed or dynamically adjustable number of channels exclusively for handoffs. For example, priority can be given to handoff by reserving N channels for handoffs among C channels in the cell [37]. The remaining $(C - N)$ channels are shared by both new calls and handoff calls. A new call is blocked if the number of channels available is less than $(C - N)$. Handoff fails if no channel is available in the candidate cell. However, this concept has the risk of underutilizing spectrum. An adaptive number of guard channels can help reduce this problem. Efficient usage of guard channels requires the determination of an optimum number of guard channels, knowledge of the traffic pattern of the area, and estimation of the channel occupancy time distributions.

Queuing of Handoff — Queuing is a way of delaying handoff [29]; the MSC queues the handoff requests instead of denying access if the candidate BS is busy. Queuing new calls results in increased handoff blocking probability. The probability of a successful handoff can be improved by queuing handoff requests at the cost of increased new call blocking probability and a decrease in the ratio of carried-to-admitted traffic since new calls are not assigned a channel until all the handoff requests in the queue are served. Queuing is possible due to the overlap region between the adjacent cells in which MS can communicate with more than one BS.

If handoff requests occur uniformly, queuing is not needed; queuing is effective only when handoff requests arrive in groups and traffic is low for two reasons. First, if there is a lot of traffic, it is highly unlikely that a queued handoff request will be entertained. Second, when there is moderate traffic and traffic arrives in bundles, a queued handoff request is likely to be entertained due to potential availability of resources in the near future and the lower probability of new handoff requests in the same period.

Queuing is very beneficial in macrocells since the MS can wait for handoff before signal quality drops to an unacceptable level. However, the effectiveness of queuing decreases for microcells due to stricter time requirements. The combination of queuing and channel reservation can be employed to obtain better performance [38].

Joint optimization of queuing and handoff parameters may be better due to the following reasons [34]:

- When handoff algorithms are designed to minimize the number of unnecessary handoffs, excessive call drops may occur during high traffic intensities. These strategies minimize the number of handoff attempts per boundary crossing, and sufficient time may not be available for entertaining handoff requests under heavy traffic conditions. For example, if a large amount of hysteresis is used to minimize handoffs, call quality may become unacceptable by the time a handoff request is entertained.
- Different handoff algorithms introduce different delays in handoff requests. Hence, the delay associated with handoff queuing may not be acceptable for some handoff algorithms. The performance improvement achievable with handoff queuing is variable and dependent on handoff algorithms.
- Some handoff requests may demand higher priority in a queue to save the call. This can be investigated properly by noting both the traffic and transmission characteristics.

Handoff Priority Schemes

Reference [34] investigates performance of different handoff priority schemes using a simulation model that incorporates transmission and traffic characteristics. The priority scheme of GSM has been evaluated. The simulation results show that the queuing and channel reservation schemes improve the dropout performance significantly, and the priority schemes provide up to 16 percent further improvement.

Reference [36] presents a handoff prioritization scheme to improve service quality by minimizing handoff failures and spectrum utilization degradation. If all the channels are occupied, new calls are blocked while handoff requests are queued. The handoff queue is dynamically reordered based on the measurements. The performance of the proposed handoff priority technique has been evaluated through simulations and compared with nonprioritized call handling and the first in first out (FIFO) queuing scheme. The proposed scheme is shown to provide lower probability of forced termination, less call blocking, less reduction in traffic, and less delay than the FIFO scheme under all traffic conditions. The new proposed scheme improves the probability of forced termination at the cost of some increase in call blocking and decrease in the ratio of combined to offered traffic. The priorities are defined by the RSS at the MS from the current BS. The degradation rate in service due to queuing depends on the velocity of the MS, and the proposed method takes this degradation rate into account.

Reference [37] discusses two methods of giving priority to handoffs in a mobile system with *directed retry*, a feature of a cellular system which allows the user to use a free channel in one of the neighboring cells [39]. Directed retry decreases the call blocking probability by sacrificing the handoff failure rate because there are fewer channels available for handoff in the candidate cell. This article presents simulation results of two handoff priority methods for a cellular system with directed retry.

Handoff and Other Resource Management Tasks

Introduction to Resource Management

Some of the radio resource management tasks performed by cellular systems include admission control, channel assignment, power control, and handoff [40, 41]. An integrated radio resource management scheme can make necessary trade-offs between the individual goals of these tasks to obtain better performance. Integrated radio resource management can increase system capacity within specified quality constraints. Due to the time- and space-varying nature of the cellular system, the radio resource management tasks need to be adaptive to factors such as interference, traffic, and propagation environment. Adaptive radio resource management tasks can reduce the initial cell planning and make replanning easier, organized, and automatic. Some of the important objectives of resource management are global minimization of the interference level and handoffs and adaptation to varying traffic and interference scenarios. A combination of individual radio resource management tasks is also possible. For example, handoff and channel assignment tasks can be combined [42]; a handoff request can be queued, and handoff is made when a channel becomes available. It should be noted that traditional cell planning may not be able to utilize the available spectrum efficiently due to highly environment-dependent radio propagation, rapid and unbalanced growth of the radio traffic, and other factors [41]. The radio resource management tasks are explained next.

Admission Control — New calls and continuing calls can be treated differently. New calls may be queued. Handoffs may be prioritized. It is important to prevent the system from being overloaded. On the other hand, capacity is revenue for service providers, and part of the perceived service quality can be attributed to the accessibility of the network.

Channel Allocation — Reference [35] provides a tutorial on channel assignment (or allocation) strategies. Channel assignment strategies can be classified into fixed, dynamic, and flexible.

Fixed channel assignment (FCA) permanently assigns a set of channels to each cell in a cluster. Some variations of the basic FCA strategy are FCA with borrowing (FCAB), FCA with hybrid assignment (FCAHA), and FCA with borrowing-with-channel-ordering (FCABCO). In FCAB, a channel can be borrowed from a neighboring cell if all the channels in a cell are busy (provided that this does not result in excessive interference). In FCAHA, channels in each cell are divided into two groups, one reserved for local use and the other kept for lending purposes. FCABCO extends the idea of FCAHA by dynamically varying the ratio of local to borrowable channels. Reference [43] compares the performance of FCA and FCABCO with two proposed channel assignment strategies. Simulations for a 49-cell network have been carried out under uniform and nonuniform traffic conditions.

Dynamic channel assignment (DCA) makes all the channels in a cluster available for use within a cluster. The actual channel assignment for a new call attempt is based on the minimization of a cost function that depends on future blocking probability, usage frequency of the candidate channel, and reuse distance of the channel. DCA does not require a priori frequency planning but must determine whether co-channel usage is allowed or not. If adaptation to the changing propagation and interference conditions is done in a channel allocation algorithm, such an algorithm must guarantee a safe co-channel reuse distance. Hence, a measure of interference for handoff candidate channel is required as an input to the channel allocation algorithm. Reference [44] deals with DCA using an artificial neural network (ANN). In microcells, the variations in the telephone traffic load are large compared to those in macrocells. Reference [45] proposes a DCA algorithm that adapts to these variations for a one-dimensional cellular system. The proposed algorithm maximizes the number of assigned calls and is suitable for distributed implementation. DCA gives better performance than FCA at low loads since it can adapt to traffic bursts. However, at high loads, it does not perform as well. Hence, some hybrid schemes have been suggested.

Flexible channel assignment (FLCA) distributes some channels among the cells in a cluster permanently and keeps the remaining channels for any cell's use when that cell's permanent channels are inadequate to cope with high traffic demand.

As explained in the previous section, the use of guard channels exclusively for handoff requests results in under-utilization of the scarce channel resources. Reference [46] presents a channel allocation algorithm that follows a *most critical first policy* in which a free channel is assigned to the handoff request which would be the first to be cut off if no channel were available at that time. Simulation results indicate that this algorithm is effective in reducing handoff failures. Reference [47] describes signal strength based distributed channel assignment schemes for a one-dimensional cellular system.

Power Control — Power control helps increase battery life, reduce health hazards, and contain interference. One way to exercise power control is to use SIR as a criterion. In this case, MSs try to attain a target SIR through continuous power adjustments. If the minimum possible power that meets the required C/I constraint at the receiver is transmitted, spectrum efficiency increases (compared to the case of uncontrolled transmit power). Increasing the transmit power (to improve C/I for better transmission quality) does not necessarily meet the objective since other transmitters in the system may also increase their power levels to reduce the interference caused to them, thus increasing the global interference level. This phenomenon is called the *party effect*.

Handoff — One of the easy solutions to BS assignment is to assign the MS to the nearest BS. Intercell handoff can be viewed as an adaptive method of preserving the planned cell boundaries and subsequently reducing the interference. Adaptation to the spatial distributions of radio traffic (or interference) can be done by modifying cell areas and shapes dynamically by adapting the handoff parameters. This effect is called *cell breathing*. In the directed retry method, if the best BS is not available, the second best BS is tried for handoff. However, directed retry increases the effectively used cell areas, increasing the global interference level.

Resource Management Integrated Handoff Algorithms

Some algorithms that combine two or more radio resource management tasks are described next.

Combined Intracell Handoff and Channel Assignment — Channel allocation algorithms that adapt to the instantaneous interference and traffic situation can lead to an easier planning process. This is a tremendous advantage since the system grows stepwise with the traffic demand in most cases [10].

Reference [10] proposes an adaptive channel allocation algorithm that is adaptive to traffic and interference. It assumes that C/I of the current channel is measured periodically. This algorithm consists of several steps, which are outlined below.

- For a new call setup or intercell handoff, reassignment is performed. In other cases, reassignment is performed if C/I_{old} for the current channel is less than a threshold C/I_{check}.
- Since it may not be feasible to calculate C/I for all the channels, channels are checked until a channel with good C/I is found. This channel is taken as a candidate channel.
- If C/I of the candidate channel, C/I_{cand}, and C/I_{old} are less than a threshold, C/I_{block}, the call is blocked.
- In the absence of call setup or intercell handoff, the candidate channel is accepted only if C/I_{cand} exceeds C/I_{old} by some hysteresis value.

An Uplink SIR-Based Integrated Handoff Algorithm — Reference [40] proposes an integrated resource management based on four SIR thresholds. The resource management tasks incorporated into the algorithm are *admission control*, *power control*, *handoff*, and *channel allocation*. A call is dropped when the SIR drops below γ_{drop}; for example, 16 dB for Advanced Mobile Phone System (AMPS). γ_{drop} is considered the minimum tolerable SIR for acceptable speech quality. Power control is achieved by a target SIR threshold γ_t. Each MS tries to attain γ_t through power control. Call admission control is achieved by an SIR threshold γ_{new}. A new call attempt succeeds only if it can offer an SIR higher than γ_{new}. This SIR threshold ensures that the system is not packed too tightly; otherwise, it may be difficult to find free channels for handoff. Moreover, a new call, if admitted, will not cause severe interference to existing calls. *Handoff* and *channel assignment* are combined in the sense that handoff is made to the minimum interference channel when SIR drops below γ_{ho}.

An RSS-Based Integrated Handoff Algorithm — The algorithm proposed in [41] uses RSS and a transmission quality measure for the channels as handoff criteria. BS allocation, channel assignment, and power control are treated in an integral manner. A new BS is selected in the case of a new call setup, and intercell handoff is based on signal strength and possibly some network criteria. The comparison between the candidate BSs is done under equal transmit power levels. Power control is performed to increase spectral efficiency.

An Integrated Power Control and Handoff Algorithm — Reference [48] treats power control and BS assignment issues in an integral manner. The objective is to find a combination of BS assignment and transmit power to provide a feasible solution to the minimum transmit power (MTP) problem. An algorithm called *minimum power assignment* (MPA) is proposed which iteratively solves the MTP problem. During an iteration of the algorithm, an MS chooses a combination of BS and transmit power for which minimum power is needed to maintain an acceptable C/I (assuming that the other MSs transmit fixed powers at the same time).

Reference [49] also proposes a similar combined power control and BS selection algorithm to achieve higher capacity in a spread-spectrum cellular system. The proposed algorithm adapts transmit powers of users and switches users between the BSs to minimize interference. The algorithm also reduces traffic congestion in a cell by moving the users to less congested adjacent cells.

Handoff Protocols

There are four basic types of handoff protocols: network-controlled handoff (NCHO), mobile-assisted handoff (MAHO), SHO, and mobile-controlled handoff (MCHO). As the handoff decision making process is decentralized (i.e., moving from NCHO to MCHO), handoff delay (i.e., the time required to execute a handoff request) decreases, but the measurement information available to make a handoff decision also decreases. These protocols are briefly described next.

Network-Controlled Handoff

In an NCHO protocol, the network makes a handoff decision based on measurements of the RSSs of the MS at a number of BSs. Sometimes the network sets up a bridge connection between the old and new BSs and thus minimizes the duration of handoff. In general, the handoff process (including data transmission, channel switching, and network switching) takes 100–200 ms and produces a noticeable click in the conversation. This click is imperceptible in a noisy voice channel; however, it is perceptible when handoff occurs at a reasonable signal quality [50]. Information about the signal quality for all users is located at a single point (the MSC). This information facilitates resource allocation. According to [51], the overall delay can be of the order of 5–10 s. This type of handoff is not suitable for a rapidly changing environment and a high density of users due to the associated delay. NCHO is used in first-generation analog systems such as AMPS, Total Acceses Communications System (TACS), and Nordic Mobile Telephone (NMT) [50].

Mobile-Assisted Handoff

An MAHO protocol distributes the handoff decision process. The MS makes measurements, and the MSC makes decisions. According to [51], there can be a delay of 1 s; this delay may be too much to counteract the corner effect.

In GSM, the BS subsystem (BSS) includes a base transceiver station (BTS) and a base station controller (BSC) [52]. The BTS is in contact with MSs through the radio interface and includes radio transmission and receiver devices and signal processing. The BSC is in contact with the network and is in charge of the radio interface management, mainly the allocation and release of radio channels and handoff management. One BSC serves several BTSs, and several BSCs are connected to one MSC. The handoff time (the time between handoff decision and execution) in GSM is approximately 1 s [3]. If the serving and target BTSs are located within the same BSS, the BSC for the BSS can perform handoff without the involvement of the MSC. This is referred to as *intra-BSS handoff*. When the MSC coordinates the handoff process, such handoff can further be classified as *intra-MSC* (within the same MSC) or *inter-MSC* (between MSCs) [53]. GSM-based handoff algorithms are evaluated in [19, 54–56].

An Interim Standard 95 (IS-95)-based system uses SHO in conjunction with MAHO. SHO is a “make before break” connection, that is, the connection to the old BS is not broken until a connection to the new BS is made. SHO utilizes the technique of macroscopic diversity. There are several variations of SHO. The term *soft handoff* is used when old and new BSs belong to two different cells. The term *softer handoff* is used when the two signals correspond to the two different sectors of a sectorized cell [57]. When soft and softer handoffs occur simultaneously, the term *soft-softer handoff* is used. As far as the MS is concerned, there is no difference between SHO and softer handoff. For the network, additional hardware overhead is required for soft handoff. One channel element hardware and one BS-to-MSC trunk are required for each cell involved in SHO. Additional frame-by-frame selection diversity is also required at the switch. No additional hardware is required at the BS for softer handoff since the channel hardware can be configured to transmit signal to multiple sector antennas and use diversity combining techniques to process the signals from multiple sector antennas. The handoff threshold needs to be small enough to bound the overall SHO percentage but large enough to allow efficient diversity combining. The MS needs more than one demodulator to exploit diversity combining techniques. SHO can increase the capacity if exercised carefully. SHO has an advantage of changing SIR distribution. The MSs far from a BS receive more signal energy, which reduces outage probability. Another advantage of SHO is that increased signal energy reduces the switching of the call between the BSs. This reduces the computational load. In particular, proper selection of the SHO region and its associated parameters can avoid the ping-pong effect common in hard handoff [58]. A disadvantage of SHO is that the mobile undergoing SHO occupies channels between different BSs and the switch (MSC). Moreover, SHO tends to increase the traffic in the wired channels in a fixed network. The greater the number of BSs involved in SHO, the more the traffic in the fixed network. SHO algorithms are focus of [57–59].

Mobile-Controlled Handoff

In MCHO the MS is completely in control of the handoff process. This type of handoff has a short reaction time (on the order of 0.1 s) and is suitable for microcellular systems [51]. The MS does not have information about the signal quality of other users, but handoff must not cause interference to other users. The MS measures the signal strengths from surrounding BSs and interference levels on all channels. A handoff can be initiated if the signal strength of the serving BS is lower than that of another BS by a certain threshold. The MS requests the target BS for a channel with the lowest interference.

MCHO is the highest degree of handoff decentralization. Some of the advantages of handoff decentralization are that handoff decisions can be made fast, and the MSC does not have to make handoff decisions for every mobile, which is a very difficult task for the MSC of high-capacity microcellular systems [60].

MCHO is used in the European standard for cordless telephones, DECT [3]. The MS and BS monitor the current channel, and the BS reports measurements — RSS and bit error rate (BER) — to the MS. The C/Is of free channels are also measured. The handoff decisions are made by the MS. Both intracell and intercell handoffs are possible. The handoff time is approximately 100 ms.

Handoff Evaluation Mechanisms

Three basic mechanisms used to evaluate the performance of handoff algorithms include the analytical, simulation, and emulation approaches. These mechanisms are described here.

The Analytical Approach

This approach can quickly give a preliminary idea about the performance of some handoff algorithms for simplified handoff scenarios. This approach is valid only under specified constraints (e.g., assumptions about the RSS profiles). Actual handoff procedures are quite complicated and are not memoryless. This makes the analytical approach less realistic. For real-world situations, this approach is complex and mathematically intractable. Some of the analytical approaches appearing in the literature are briefly touched on below.

The level crossings of the difference between the RSSs from two BSs were modeled as Poisson processes for stationary signal strength measurements in [61, 62]. In [63], this analytical work was extended to nonstationary signal strength measurements, and the level crossings were modeled as Poisson processes with time-varying rate functions. The results in [61, 63] are useful for determining the averaging interval and hysteresis level to achieve an optimum balance between the

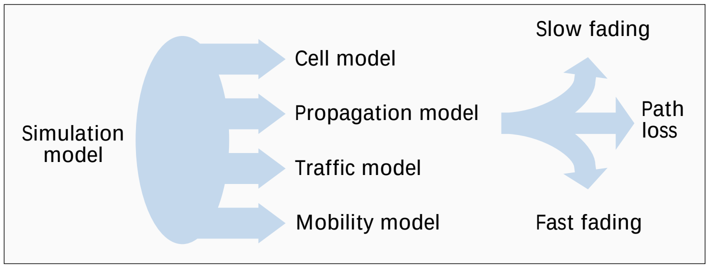


Figure 8. *Simulation model components.*

number of unnecessary handoffs and delay in handoff for a simplified scenario in which an MS travels along a straight line from one BS to another at a constant velocity. Reference [64] incorporates the effect of CCI in the signal-strength-based handoff algorithm analysis presented in [61]. Reference [65] develops an analytical model for analyzing performance of handoff algorithms based on both absolute and relative signal strength measurements and compares analytical results with simulation results. Reference [66] extends the scope of the analysis done in [65] by considering multiple BSs. Furthermore, a BS becomes a candidate only if its signal strength is strongest among all the BSs under consideration. The analytical model is verified through simulation results.

Reference [60] derives bounds for some performance measures and gives analytical expressions for the performance measures for a particular (linear) class of algorithms. Linear handoff algorithms do not use hysteresis and use only one quality measure (i.e., signal strength).

The effect of handoff techniques on cell coverage and reverse link capacity for a spread-spectrum CDMA system is investigated in [67]. The article shows that SHO increases both the cell coverage and reverse link capacity significantly compared to conventional hard handoff, and derives quantitative performance improvement measures for cell coverage and capacity of the reverse link.

In [68], prioritized handoff schemes have been analyzed. It was assumed that the probability density function (pdf) of the speed of cell-crossing terminals is the same as the pdf of the terminal speeds inside the cells. Reference [69] derives a more precise pdf using biased sampling in boundaries. The resultant analysis is computationally less complex and more accurate than the approach in [68].

An analytical model is proposed in [70] to study the traffic performance of a microcell/macrocell overlay for a PCS architecture. If a call cannot be served by a microcell, it is connected to a macrocell. The call is blocked if no channel is available in the macrocell. The overflow traffic to the overlay macrocell is computed. The residual time distribution for a macrocell is derived based on the assumed residual time distribution for a microcell. The call termination probability for the macrocell is computed using the overflow traffic as input.

Reference [71] presents teletraffic performance of a highway microcellular system with a macrocell overlay. It assumes a TDMA scheme with 10 channels/carrier and one carrier/BS. The teletraffic analysis assumes that the mobile speeds follow truncated Gaussian distribution. The probability of new call blocking and handoff call forced termination have been evaluated for three scenarios: when no priority is given to any MS, when priority is given to handoff calls, and when a macrocell overlay makes channels available to transfer calls from the MSs that would be blocked during a microcellular handoff.

The teletraffic analysis of a hierarchical cellular network (in which umbrella cells accept handoff requests that cannot be managed by microcells) is the focus of [72]. The handoff flow from a microcell to a macrocell is modeled as a Markov modulated Poisson process, and call blocking and call dropping probabilities are calculated.

The Simulation Approach

This is the most commonly used handoff evaluation mechanism. Several simulation models suitable for evaluation of different types of handoff algorithms under different deployment scenarios have been proposed and used in the literature. The simulation approach allows incorporation of many features of a cellular system and a cellular environment into the evaluation framework. This approach provides a common testbed for comparison of different handoff algorithms, and also provides insight into the behavior of the system [2]. Despite being cost-effective, measurements made at the BSs for handoff performance evaluation are not very useful since they cannot characterize small-area performance. Field measurements are useful, but they are time-consuming and expensive. Software simulation provides fast, easy, and cost-effective evaluation. The analytical approach gives insight into handoff behavior quickly, while simulations are required for complex scenarios. Hence, the combination of the analytical and simulation approaches can be very powerful. Simulation models usually consist of one or more of the following components: the cell model, propagation model, traffic model, and mobility model. These components are described first. Specific simulation models are discussed next. Figure 8 shows the components of a typical simulation model

The Basic Components of Simulation Models —

The Cell Model — Cell planning strategies differ in microcells and macrocells. The cells can be considered as circles while considering handoff between two BSs in a neighborhood of two, three, or four cells. A macrocellular system is sometimes simulated as a 49-cell toroidal system that has seven-cell clusters with uniformly distributed traffic. Reference [12] discusses microcell cell planning in the Manhattan environment. The city is modeled as a chessboard with squares representing blocks and streets located between the blocks.

The Propagation Model — The performance of wireless communication systems depends significantly on the mobile radio channel. The radio wave propagates through the mobile radio channel through different mechanisms such as reflection, diffraction, and scattering. Propagation models predict the average signal strength and its variability at a given distance from the transmitter. Different propagation models exist for outdoor and indoor propagation and for different types of environments (e.g., urban and rural) [73]. Macrocells and microcells have different propagation characteristics. Reference [74] presents signal attenuation measurements for microcells and shows that the conventional propagation models (e.g., Hata and Okumura models) are not valid for a microcell environment. The 900 MHz and 1.8 GHz signal attenuation measurements were carried out for BS antenna heights ranging from 5–20 m and an MS antenna height of 1.5 m in Melbourne, Australia. The main features of the models discussed here have been experimentally validated in the literature. For example, reference [75] suggests path loss, slow fading, and fast fading models for a microcellular system based on actual measurements. Reference [76] describes computer models of Rayleigh, Rician, log-normal, and land mobile satellite fading channels based on processing of a white Gaussian random process. The propagation model usually consists of a *path loss model*, a *slow fading model*, and a *fast fading model*.

- The path loss model: In macrocells, the path loss model is used for several aspects of cell planning such as BS placement, cell sizing, and frequency reuse [9]. The path loss models of Hata and Okumura can be used for macrocells. Microcells have different models for LOS and NLOS propagation.

For *LOS propagation*, two frequently used models are a *flat*

Earth model and a *two-slope model*. In the *flat Earth model*, one direct ray and another reflected ray (with 180° phase shift) contribute to the total received E-field. In reference [75], an empirical path loss two-slope model is suggested. The path loss increases with a certain slope to a threshold distance (called a *breakpoint*) and then increases with a higher slope. In reality, wave propagation in microcells is complicated and consists of reflections and diffractions in addition to free space propagation. However, the main features of path loss can still be described by these empirical models. For certain parameter settings, the two-slope path loss model approaches the flat-earth model.

For *NLOS propagation*, LOS propagation is assumed to the street corner. After the corner, propagation path loss is calculated by placing an imaginary transmitter at the corner with the transmit power equal to the power received at the corner from the LOS BS.

- The slow fading or large-scale fading model: According to [75], the distribution of the slow fading component is close to a log-normal distribution for a majority of LOS and NLOS streets with different standard deviations. The distribution is actually a truncated log-normally distributed variation. In simulations, the variation should not be greater than $\pm 3\,\sigma$. For the measurements obtained in reference [75], the average value of σ was found to be 4 dB for LOS streets and 3.5 dB for NLOS streets. Reference [77] proposes an exponential autocorrelation model for shadow fading in mobile radio channels. The results show that the model fit is good for moderate and large cells; the predictions are less accurate for microcells due to multipath.
- The fast fading or small-scale fading model: Fast (or short term) fading is usually modeled as a Rician distribution where parameter K (Rice factor) varies with distance. When $K = 0$, the variation is Rayleigh fading. Reference [75] suggests a fast fading model in terms of polynomials based on the Rician distribution. Fast fading can usually be neglected since it gets averaged out due to a short correlation distance relative to that of shadow fading.

The Traffic Model — Traffic can be assumed to be uniform for macrocells. However, road structures need to be considered for microcells, and traffic can be allowed only along the streets. The new call arrival process is modeled as an independent Poisson process with a certain mean arrival rate. The new call durations are independent exponential random variables with a certain mean. In some simulation scenarios, the statistics of dwell time can be useful [78]. Dwell time is defined as the average time spent by an MS in a cell without handoff.

The Mobility Model — The MSs have different velocities following a truncated Gaussian distribution.

***Specific Simulation Models* —** A brief account of widely used simulation models is given here.

References [42, 60, 61, 63, 79, 80] use a two-BS model that is simple and widely used for evaluating signal-strength-based algorithms. This model is suitable for small-size macrocells and LOS handoffs in microcells. In this model an MS travels from one BS to another in a straight line at a constant velocity. The path loss is calculated using a single-slope formula, and shadow fading is assumed to be log-normal with an exponential correlation function.

A model suitable for evaluating the performance of signal-strength algorithms is used in [55, 56]. The model has a four-cell neighborhood, and the MS travels from one BS to another in a straight line with constant velocity. The model assumes that there is no power control, and all BSs transmit at the same power level. The path loss is calculated using Hata's model, and shadow fading is log-normally distributed. Reference [81] has a three-cell instead of the four-cell neighborhood in [55, 56].

Two routes of an MS in a cluster of seven cells are considered in [54]. The first route is from one BS to another in which the MS crosses cell borders such that it is inside the overlapping region for a minimum duration of time. This route gives insight into the behavior of the handoff algorithm in the handoff area. The second route is from one BS to another in which the MS is in the overlapping region most of the time. This second route is more hostile than the first in terms of handoff complications. The four-cell model of [55] can easily be modified to create these two MS routes by adjusting the cell radii.

Reference [82] uses an SIR-based model that can be used for integrated dynamic resource management tasks. Twenty BSs are uniformly spaced on a ring. The traffic model and mobility models used in [82] are the same as described earlier. The new calls are uniformly distributed throughout the ring.

A model suitable for evaluating LOS and NLOS handoffs in a microcellular environment is used in [83]. The LOS and NLOS propagation models are similar to those described earlier. The log-normal shadow fading with exponential correlation function for slow fading and Rician fading model for fast fading are used.

The model of [3] is suitable for a microcellular environment. Two NLOS paths are considered which give insight into the behavior of handoff algorithms when there are multiple street crossings. The effect of C/I is studied in [3] for a particular cell plan. A worst-case scenario (i.e., C/I of 12 dB) is used to account for interference. Reference [3] also studies the C/I distribution for the MS and BS.

A comprehensive model for a microcellular system is presented in [41]. This reference considers a Manhattan-like structure and places a BS at every other corner. At every street crossing, an MS either goes straight or turns with a given probability. The model is formed into a torus-like structure to avoid edge effects. The LOS propagation model is taken from [74]. For the NLOS model, it is assumed that buildings are infinitely tall, and there is a fixed loss of 20 dB every diffraction street corner. Shadow fading is not considered, but fast fading is modeled as Rayleigh fading.

A comprehensive simulation model suitable for macrocellular and microcellular environments is described in [84–86]. The conventional macrocellular environment is modeled by a 49-cell toroidal structure that has seven-cell clusters with 1 km radius cells [87]. The microcellular system has half-square cells with 100 m block size. The simulation model for a microcell system considers both the transmission and traffic characteristics. Such combined analysis of transmission and traffic characteristics provides a more realistic scenario for performance evaluation of a cellular system. Reference [88] gives a brief account of the simulation model (called *M2 simulation*) developed at AT&T; this model includes the effects of propagation, traffic, and system configuration.

The model of [38] is suitable for evaluating handoff performance in a mixed-cell environment. An urban Manhattan-like environment is simulated in which a cluster consists of four microcells. Four clusters cover the service area with a macrocell overlaying the microcells. User mobility has been modeled as Gaussian with the mean value varying with the distance from the starting position of the MS. A sharp linear velocity decrease is adopted before turning, and a linear increase has been considered after the corner until the previous velocity is restored. The path loss is calculated using the two-slope law. Second and fourth powers are used. The street corner is simulated by a 4 dB/m linear decrease from the street corner and lasting up to 20 m. After that an NLOS propagation is assumed. Slow fading is simulated by uncorrelated log-normal distribution. New calls follow a Poisson model and are uniformly distributed along the streets.

The Emulation Approach

The emulation approach uses a software simulator consisting of a handoff algorithm to process measured variables (e.g., RSS and BER). Actual propagation-measurements-based simulation has the advantage of giving better insight into the behavior of the radio channels and more accurate data. The main disadvantages are that this approach requires periodic measurement efforts and is not suitable for comparison of different handoff algorithms on the same platform.

Reference [11] uses measured data in handoff simulation (the measured data was obtained by conducting 1700 MHz experiments in an urban environment in southern England). The path loss was found to follow a two-slope formula with different slopes for different locations. The short-term fading was found to be Rician with Rice factors varying from 10 to zero depending on the distance between the MS and BS. It was found that the optimal handoff threshold level was different for different sites [11].

Reference [89] introduces an indoor propagation simulator. The indoor simulator models trace 13 rays over a cross-corridor and exhibit good agreement with the experiments of 950 MHz propagation with multipath fading.

Reference [90] describes an experimental digital cellular system that consists of a private branch exchange (PBX)-based MSC, three BSs, two MSs, and a radio channel simulator. Experimental results indicate that a handoff decision can be made within 1 s, and the handoff procedure works well under typical microcell propagation conditions.

Conclusion

Handoff is an integral component of cellular communications. Efficient handoff algorithms can enhance system capacity and service quality cost effectively. Different system deployment scenarios present different constraints on handoff procedure. Handoff algorithms with a specific set of parameters cannot perform uniformly well in different communication system deployment scenarios since these scenarios impose distinct restrictions and peculiar environments on the handoff process. Such system scenarios are illustrated. These system structures are expected to coexist in future wireless communication systems and warrant substantial study. Handoff prioritization can improve handoff-related system performance. Two basic handoff prioritization schemes, guard channels and queuing, are discussed. Handoff represents one of the radio resource management tasks carried out by cellular systems. Some other resource management functions include admission control, channel assignment, and power control. If the resource management tasks are treated in an integral manner, better overall performance can be obtained to achieve global goals by making appropriate trade-offs. Such integrated resource management is discussed briefly. Different systems use different approaches to execute the process of handoff, and handoff protocols that characterize these approaches are explained. Several mechanisms can be used to evaluate handoff-related system performance; three such mechanisms are described in detail.

Acknowledgments

The authors are grateful to Dr. Ravi Jain of Bellcore, Dr. Magnus Almgren of Ericsson, Dr. Sirin Tekinay of New Jersey Institute of Technology, and the referees of the article for their helpful suggestions.

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