Wireless Personal Communications (2006) 39: 515–542
DOI: 10.1007/s11277-006-9096-8

Dropping Rate Reduction in Hybrid WLAN/Cellular Systems by Mobile Ad Hoc Relaying

PEJMAN KHADIVI, SHADROKH SAMAVI, HOSSEIN SAIDI, TERENCE D. TODD and DONGMEI ZHAO

Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran, and McMaster University, Hamilton, Ontario, Canada
E-mail: samavi@mcmaster.ca

Abstract. Future mobile handsets will often be multi-mode, containing both wireless LAN (WLAN) and cellular air interfaces. When such a device is within a WLAN it can be served by the WLAN resources. As it moves out of the WLAN coverage area, it has to be served by the cellular system. Therefore, handoffs are necessary between the WLAN and the cellular system. In loosely coupled WLAN/Cellular systems the system administrator of the WLAN is different from the cellular one. Therefore, in these situations, reducing the dropping probability based on classical methods, such as using some reserved guard channels, is difficult. In this paper, we propose to use ad hoc relaying during the vertical handoff process in a hybrid WLAN/Cellular system. The method that we propose in this paper improves the dropping probability regardless of the number of reserved channels. Therefore, this method could be employed in loosely coupled hybrid systems. Both analytical reasoning and simulation results support the effectiveness of the proposed method.

Keywords: dropping rate, Ad Hoc networks, hybrid wireless networks

1. Introduction

Recently, some proposals have been presented in the literature to build hybrid structures out of different wireless systems. *Wireless local area networks* (WLANs) support broadband multimedia communications in a wireless manner. Because of their high bandwidth, low latency and ease of deployment, WLANs are suitable for public wireless communications. In the past decade there has been a huge proliferation of WLANs based on the IEEE 802.11 standard [1]. As the cost of 802.11 based components decreases, wireless manufacturers will increasingly incorporate these devices into the cellular handsets. Seamless real-time voice operation is a highly desirable capability for these types of handsets. The importance of WLANs is such that the *Third Generation Partnership Project* (3GPP) builds up a standard architecture for cooperating cellular-WLAN systems. The main motivation is to enable 3GPP system operators to provide public WLAN access as an integral component of their services. Future mobile handsets will often be multi-mode, containing both WLAN and cellular air interfaces [2, 3].

Handoff in the traditional cellular systems is a well-known problem. With co-operation between different types of wireless networks, vertical handoffs will commonly be used to pass voice calls to a cellular network when the user roams outside of the WLAN radio coverage. Therefore, different aspects of vertical handoff need special attention.

In the next-generation hybrid mobile networks, one of the most important issues is the seamless vertical handoff [4]. While seamless handoff issues such as handoff delay, handoff transparency and packet loss are interesting, reducing the dropping probability is another important aspect of the vertical handoff. The proposed solutions for the seamless handoff problem are applicable when the handoffs are being accepted. When an on-going call is to be dropped having a number of lost packets is not an issue.

In this paper we propose the use of the ad hoc relaying for dropping probability reduction. Ad hoc relaying has previously been used for other purposes such as capacity and/or coverage improvement. However, there has been no attempt for using the ad hoc relaying through mobile stations in order to reduce the dropping probability.

When roaming between different 802.11 WLANs, a dual-mode *mobile station* (MS) uses IEEE 802.11 layer 2 roaming procedures. When the *received signal strength indication* (RSSI) drops below a certain threshold, the MS scans for a new *access point* (AP) using standard IEEE 802.11 procedures [1]. When the MS approaches the boundary of the WLAN coverage, a new AP may not be found and at some point the MS will trigger the initiation of a vertical handoff into the cellular network.

There are two different inter-working solutions for the interoperation between a WLAN and a traditional cellular system [3]. *Tight coupling* is a method for integrating of the WLAN into a cell. This solution suggests that the WLAN and the cellular system come together to build a network managed by a single administrator. In *loose coupling*, there are not many interactions between the WLAN and the cellular network. This is a less complex solution compared with the tight coupling strategy. Currently, loose coupling is the main choice for this type of cooperation [3].

When loose coupling is used for interoperation between 802.11 WLANs and cellular systems, WLANs are installed in different locations inside the cellular coverage with no contraction with the cellular service providers. Hence, a handoff which is initiated by an MS moving out of the WLAN's coverage area may be considered as a new connection request by the cellular system. Therefore, traditional solutions for dropping rate reduction, such as *channel reservation* or *handoff queuing*, are not applicable [5, 6].

The method that we propose in this paper improves the dropping probability regardless of the number of reserved channels. Therefore, this method could be employed in loosely coupled hybrid systems. A number of methods have been suggested in the literature that use the relaying to extend the coverage area or to improve the overall capacity of a cellular system [7–12]. The same kind of handset capabilities could be used in our suggested method.

This paper is organized in the following manner: In Section 2, a short survey of the literature is presented. The proposed relaying method for dropping rate reduction is presented in Section 3. In Section 4 analytical reasoning is used to show the benefits of the proposed method. Simulation results are presented in Section 5. Section 6 is dedicated to some concluding remarks.

2. Related Works

Tremendous developments of wireless communications technology indicate the importance of research in this area. Infrastructure-based networks such as cellular GPRS and UMTS, and wireless LANs such as IEEE 802.11 are now in use around the world [1, 13–15]. Infrastructure-less types of wireless communication systems are known as ad hoc networks. In this type of networks a communication path from a source to a destination may pass through other MS's. Due to the multi-hop nature of communication, routing in these networks is an interesting subject [16–18].

Integrating the ad hoc networks with the cellular systems has been suggested in the literature [7–12, 19–22]. The main goal of this integration is to increase the system's capacity and its coverage. *Multi-hop cellular networking* (MCN) is introduced in [19]. In MCN's, the stations' transmission power and/or the number of BS's are reduced compared with the traditional single hop cellular networks. Therefore, MS's may not be able to communicate with their serving BS in a single hop and may have to use multi-hop paths. Also, when the source and destination MS's are in a same cell, they can communicate without going through the BS. It is expected that MCN's support more connections than the traditional cellular networks.

By using some pre-installed *relay stations* (RS's) it is suggested in [7] that other cells could accept some new connection requests when the current cell is congested. This strategy is named iCAR and can increase the capacity of the cellular system. In [8], relaying concept is used in a hotspot cell. The proposed method tries to *shed* some new calls to the neighboring cells or to *shrink* the cell coverage area through the relaying. Two-hop relaying through mobile nodes has been used for this purpose [8]. In [9], the concept of relaying is used for reducing the number of unnecessary handoffs. Geo-locating techniques are used to find the location of the MS's. This location information can be used in the RS selection routine. In [10], *Ad hoc GSM* (A-GSM) architecture is proposed. In A-GSM, ad hoc networking is combined with the traditional GSM cellular system. *Opportunity Driven Multiple Access* (OMDA) is another proposed method that integrates the ad hoc networking with cellular systems [11]. When there is not an overlap between neighboring WLAN's, two-hop ad hoc relaying could be used during the handoff procedure [12]. Forward and backward ad hoc relaying is used to prevent the ongoing calls from being dropped when the MS's enter such an area. In [20], rather than data, control information is relayed in order to implement a fast version of Mobile-IP.

In [21], a new MAC layer protocol, compatible with IEEE 802.11 WLAN standard is proposed for real-time traffic support in a relayed wireless environment. Also [21] proposes the required packet scheduling method and a simple call admission control algorithm for providing guaranteed QoS. It is assumed that there are at most two wireless hops in the system. The proposed MAC is completely based on the legacy IEEE 802.11 standard and an MS needs no modification to work in this new environment. While it is mentioned in [21] that the proposed protocol can support both mobile and fixed (pre-installed) relaying, the system has been evaluated for pre-installed relay stations. In [22] a number of methods are presented to choose an RS from a set of candidates. The system is actually a traditional cellular one, which is integrated with a two-hop ad hoc relaying mechanism. Different methods are presented there to select an RS based on the estimated distance or based on the path loss.

Vertical handoff and *micro-mobility* are other interesting subjects, studied in the field of mobile networking [4, 20, 23–27]. In vertical handoff, we are facing with the handoff problem between different networks. In a hybrid WLAN/Cellular system, vertical handoffs from the WLAN to the cellular system and from the cellular system to the WLAN have a great importance.

Handoffs should be transparent to the upper-layer applications. This transparency is the subject of the *seamless handoff* [4]. In seamless handoff the *packet loss* during the handoff procedure and the *handoff delay* should be minimized. Architectural issues and handoff initiation problem are addressed in [4, 24]. Packet forwarding and multicasting are proposed to reduce the number of lost packets [25–27]. Also, the effect of handoff on upper layers is addressed in [23].

Khadivi et al. [28] suggests using explicit handoff triggering for dropping rate reduction. In this method a simple handoff trigger node can be installed in the WLAN/cellular transition region. This generates link layer triggers, which cause the initiation of the vertical handoff process. The method is applicable for indoor environments.

In [29] we have shown that the dropping probability reduction during the handoff from the WLAN to the cellular system is possible through ad hoc relaying. Two-hop and multi-hop ad hoc relaying methods were introduced and compared with the simple legacy handoff strategy through simulations.

In the following sections, the effect of two-hop ad hoc relaying on the dropping rate is studied through analytical reasoning and simulations.

3. Dropping Reduction Through Ad Hoc Relaying

Let us assume that a WLAN is used to cover a hotspot area. An access point serves the mobile stations inside the WLAN. Also, it is assumed that the MS's are multi-mode. Therefore, each MS has at least two different air interfaces for working with the cellular system and the WLAN [7–12, 28]. In this section, we are going to describe the proposed ad hoc relaying model and its application in dropping rate reduction. Some key definitions come in the following paragraphs, which are used in the remainder of the paper.

Definition **1** An *active mobile station* is the one which has an active connection with either the WLAN or the cellular system. Otherwise we call the mobile station as *non-active.*

Definition **2** When an active MS is served by the WLAN through a one-hop connection, we say that the MS is in the *WLAN mode.* An active MS which is served by the cellular system is in the *Cellular mode.*

Definition **3** Assume that an active MS is being served by the WLAN. If this MS moves out of the WLAN's coverage area, a *WLAN-to-Cell handoff* is initiated. Other types of handoff that may occur are *WLAN-to-WLAN, Cell-to-Cell* and *Cell-to-WLAN* handoffs.

Let us consider an MS that initiates a WLAN-to-Cell handoff. Due to limited capacity in the cellular side, there is a probability of call dropping. If the hybrid system is a loosely coupled one, traditional methods for dropping rate reduction are not easily applicable. One of the main reasons is that the handoff requests are considered as new-connection ones by the cellular system's BS. When a handoff is initiated by an active MS there are a number of non-active MS's inside the hotspot. The active MS can use these non-active ones as relay stations and through relaying it can stay connected with the original AP.

When an active MS leaves the hotspot, it sends a handoff request to the BS. Handoff can be completed successfully when the BS has at least one free channel. When the handoff request is rejected the MS tries to find an RS. When the RS has been found the MS can relay its connection back to the AP. While being served by the AP through the ad hoc relaying the MS can repeat its handoff request. Hence, it has more chance to find a free channel in the cellular system. The immediate result is a reduction in the call-dropping rate. An example is illustrated in Figure 1. In *ad hoc relaying handoff* (RHO) model, one RS is used for a single connection and hence, the relaying path is 2-hop.

When an MS is going to use the RHO, it must find a suitable relay station. Here, it is assumed that only the *non-active mobile nodes* may be used for the relaying purpose. Obviously, the RS must be inside the hotspot's coverage area. In the following we have a formal definition of a *potential RS:*

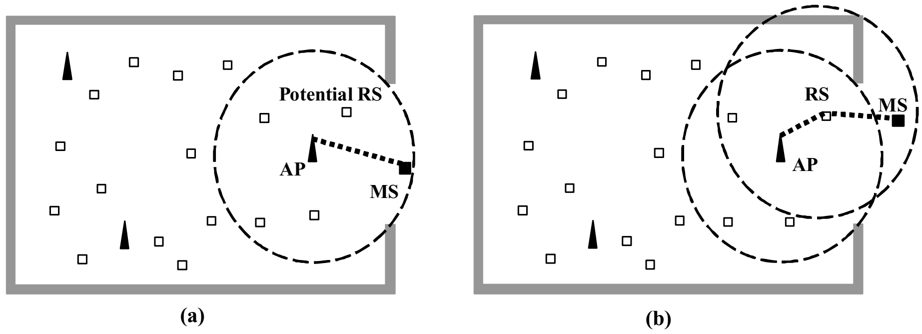


Figure 1. An example of ad hoc relaying. (a) Handoff initiation with no available channel (b) Two-hop ad hoc relaying through an RS.

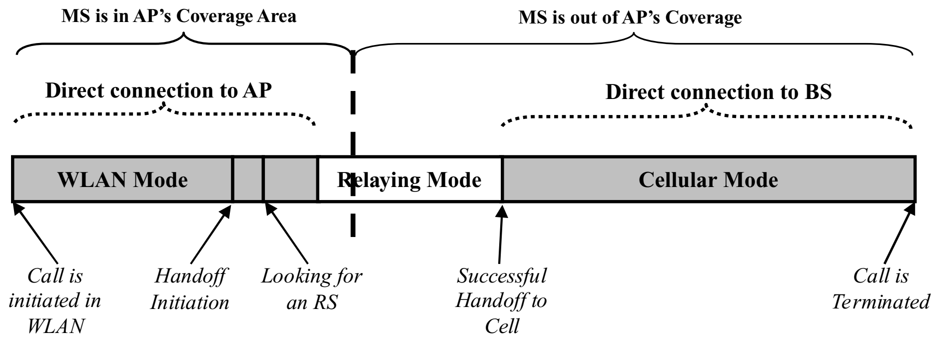


Figure 2. Different modes of an active MS when the RHO is in use. Dashed line represents the WLAN's border.

Definition **4** A non-active mobile station is called a *Potential RS* if and only if, it is located inside the hotspot coverage area.

When relaying is employed in a hybrid wireless network with multi-mode devices, each MS may work in different modes. While the *WLAN* and *Cellular* modes are previously defined, in the following we state what we mean by the *Relaying mode:*

Definition **5** When an active MS, outside the hotspot, is served by the WLAN through a relay station, we say that the MS is in the *relaying mode.*

Figure 2 shows how an active MS may be in different modes when the RHO is in use. At first the MS is in the WLAN mode, served directly by the WLAN's AP. When the received signal strength indication (RSSI) drops below a certain threshold, a handoff is initiated. If the handoff request is rejected by the cellular system, the MS looks for an RS. The MS goes into the relaying mode when an RS is found. When the handoff to the cellular system is completed successfully the MS is directly connected to the cellular system and works in the Cellular mode.

The distance between an active MS, which is in the relaying mode, and its serving RS must be less than a certain value, otherwise, they can not communicate. We name this certain value as the *relaying transmission range* and it is defined as follows:

Definition **6** The maximum permitted distance between an active MS, in the relaying mode, and its serving RS is called as the *relaying transmission range.*

In the following section, through analytical reasoning, we show how the coverage area is extended through ad hoc relaying and how this extension could be helpful in the dropping rate reduction.

4. Analytical Reasoning

In the previous section, we define the ad hoc relaying model and its application in handoff from a WLAN to a cellular system. In this section, we are going to study the effects of this strategy on the dropping rate reduction, through an analytical reasoning.

Let us assume that the hotspot's original coverage area is a circle with radius r centered at the AP. Without ad hoc relaying only mobile stations inside this circle can communicate with the AP. Ad hoc relaying connects MS's outside the WLAN's coverage area to the corresponding AP. Furthermore, assume that the *relaying transmission range* is equal to ρ. Then, the mobile stations that are at most $r + \rho$ away from the AP could be served by the WLAN's resources. This situation is illustrated in Figure 3. The mobile station at point *A* is directly connected to the AP and is working in WLAN mode. The MS at point *C* needs to be in the relaying mode if it is to be served by the WLAN.

It is important to notice that when an MS wants to be served by a WLAN through relaying, appropriate RS's must be available. The maximum distance between the MS and AP during the relaying process depends on the location of the MS and the potential RS's. Therefore, when the MS at point *D*, in Figure 3, communicates with the AP through the RS at point *E*, the maximum distance between *D* and AP is less than $r + \rho$.

Let us consider the situation which is illustrated in Figure 4. Assume that an active MS is located at point *B* and is moving on a straight line out of the hotspot with a constant velocity, v. While the MS is inside the WLAN's coverage area, it is in the WLAN mode. When the MS is at point Cl, its distance from the AP is r. The RSSI drops below a certain threshold and the MS initiates a WLAN-to-Cell handoff. When the active MS reaches point *C2*, where the distance from AP is $r + \Delta$, the direct link with the AP is severed. With the *legacy handoff strategy* (LHO), a successful handoff must be completed before the MS arrives at point *C2*, otherwise, a connection drop occurs [28]. With the ad hoc relaying handoff strategy, the MS can be connected to the AP when it is outside of the hotspot coverage area. Let us assume that

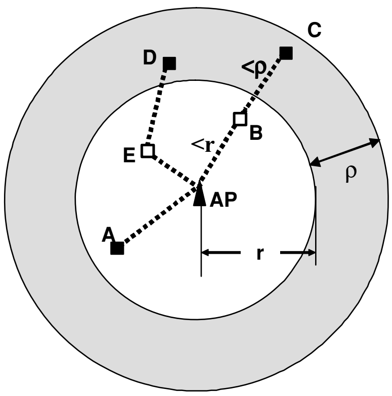


Figure 3. Extension of the coverage area through RHO strategy.

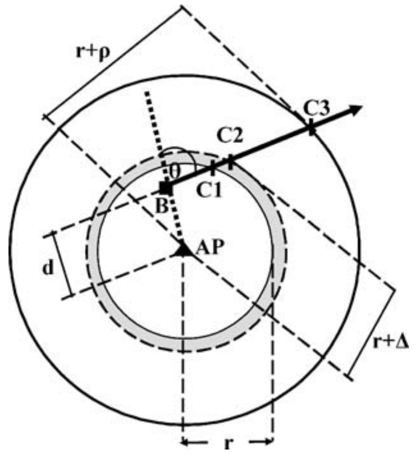


Figure 4. Extension of a WLAN coverage area by 2-hop relaying.

by the ad hoc relaying, an MS can communicate with the AP through other nodes while the distance between the AP and the MS is less than $r + \rho$. Based on Figure 4, we have:

$$\begin{aligned} D_1 &= \text{dist}(B, C1) = -d\cos\theta + \sqrt{r^2 - d^2\sin^2\theta} \\ D_2 &= \text{dist}(B, C2) = -d\cos\theta + \sqrt{(r+\Delta)^2 - d^2\sin^2\theta} \\ D_3 &= \text{dist}(B, C3) = -d\cos\theta + \sqrt{(r+\rho)^2 - d^2\sin^2\theta} \end{aligned} \quad (1)$$

where, dist(X, Y) is the distance between points X and Y. Also d is the distance between the AP and B. Therefore, it is obvious that if:

$$r < r + \Delta < r + \rho \quad (2)$$

then we will have:

$$D_1 < D_2 < D_3 \quad (3)$$

Now, let us define:

$$T_i \hat{=} \frac{D_i}{\nu} \quad (4)$$

where T_i is the time that it takes for the MS to move from B to Ci, $i = 1, 2, 3$. Based on (3) and (4):

$$T_1 < T_2 < T_3 \quad (5)$$

In the following paragraphs we analyze the effects of the ad hoc relaying on the call dropping rate for an extreme case. Then, in the next subsection, a simple analytical model is proposed in order to determine the effects of different parameters on the performance of the relaying strategy.

Let us assume that the cellular channels are fully occupied. We also assume that there will not be any free channel in the near future. Therefore, under non-relaying policy, an active connection will be dropped, when the MS is at point *C2* (Figure 4). On the other hand, with the ad hoc relaying, the active connection is not dropped until the MS reaches point *C3*.

It is obvious that if the call duration is going to be long enough, it will eventually be dropped. Consider that $T_{\max}$ is the maximum allowable call duration of an active connection. Furthermore, we assume that the connection has been started T_0 seconds before the MS leaves point B. Then, for the non-relaying strategy we have:

$$T_{\max}(\text{non} - \text{relaying}) = T_0 + T_2 \tag{6}$$

and when the ad hoc relaying is being used:

$$T_{\max}(\text{relaying}) = T_0 + T_3 \tag{7}$$

Based on (5), (6) and (7):

$$T_{\max}(\text{relaying}) > T_{\max}(\text{non} - \text{relaying}) \tag{8}$$

Assume that the call duration is equal to t seconds. Then, the mentioned connection is terminated successfully if and only if, $0 \leq t \leq T_{\max}$. If t is an exponentially distributed random variable with parameter μ we have:

$$p_s = P(0 \leq t \leq T_{\max}) = \int_0^{T_{\max}} \mu e^{-\mu t} dt = 1 - e^{-\mu T_{\max}} \tag{9}$$

where, p_s is the probability of a successful call termination. Hence,

$$\begin{aligned} p_S(\text{non} - \text{relaying}) &= 1 - e^{-\mu(T_0+T_2)} \\ p_s(\text{relaying}) &= 1 - e^{-\mu(T_0+T_3)} \end{aligned} \tag{10}$$

Therefore, based on (5), (8) and (10):

$$p_s(\text{relaying}) > p_s(\text{non} - \text{relaying}) \tag{11}$$

and hence the probability of a successful call termination will be higher in the relaying case, which results in a lower dropping probability. In the next subsection, a simple analytical model is proposed to compare the dropping probability of the LHO and the proposed RHO strategies.

4.1. Simple Analytical Model

In the following paragraphs, a simple analytical model is proposed and the dropping rate is compared between the LHO and RHO strategies. Let us assume that an MS initiates a handoff process at time t_0. Also, assume that the handoff may be completed at any time before t_T. In other words, the MS has $\tau = t_T - t_0$ seconds for a successful handoff, otherwise, the call may be dropped. Under these conditions, one of the following events may occur:

- The handoff is completed successfully at time t_1 where, $t_0 \leq t_1 \leq t_T$.
- The call is terminated successfully at time t_2 where, $t_0 \leq t_2 \leq t_T$.
- The call is dropped at time t_T.

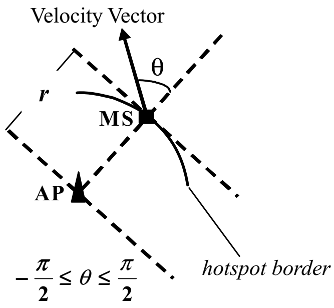


Figure 5. Movement of the MS on a straight line leaving the hotspot and not return.

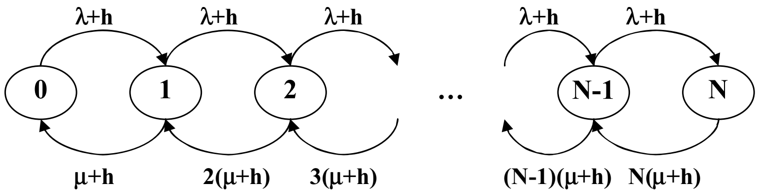


Figure 6. Simple Markov chain used to model the cellular system.

It is clear that if $t_2 \le t_0$ there is no need for handoff. Also, if $t_1 > t_T$ and $t_2 > t_T$ then the call is dropped at t_T. It is assumed that mobile stations move on straight lines with constant velocities, uniformly distributed over $[V_{\min}, V_{\max}]$. This implies that when an MS moves out of the hotspot, it will not return in the near future. This situation is illustrated in Figure 5 where the solid arrow indicates the velocity vector and the direction of movement is at most tangent to the hotspot border.

In order to model the cellular system, some simplifications are assumed, consistent with the literature [5, 6, 30]. A simple Markov process is used to model the behavior of the cellular system. The Markov chain, which is used for this purpose, is shown in Figure 6. The *call duration* is assumed to be an exponentially distributed random variable with parameter μ. It is assumed that the Cellular-to-Cellular handoffs occur with Poisson distribution with the rate of h. Also, it is assumed that new call generation rate is λ and new calls are generated with Poisson distribution. The cellular system has N channels and it is in state i if and only if, i channels are occupied. When the cellular system is in state $i, i \le N - 1$, handoff and new connection requests are admitted and there is no dropping or blocking event. Handoff requests are rejected when the cellular system is in state N. For simplicity it is assumed that there is no reserved channel for handoff requests.

It is assumed that during the time period $[t_0, t_T]$, only one WLAN-to-Cell handoff is initiated. Furthermore, it is assumed that in the RHO strategy, when the MS is inside the extended transition region, at least, one relay station is always available.

There is an important difference between the *handoff rejection* and the *call dropping* events. Let us consider the situation of Figure 4 with the LHO strategy. The handoff is initiated at point C_1 but dropping happens only when the MS is at point C_2. In Figure 4 the shaded area is the original transition region, with the width of Δ. Therefore, it takes $T_2 - T_1$ seconds for the MS to leave the transition region, where T_i is defined by (4).

Let us define τ as the time the MS has for successful handoff completion. In other words the MS remains in the transition region for τ seconds. The variable τ is a function of the velocity vector and hence a random one. Based on Figure 4 and Equations (1) and (4) we have:

$$\tau(\text{LHO}) = \frac{-r\cos(\theta) + \sqrt{(r+\Delta)^2 - r^2\sin^2(\theta)}}{\nu}$$
$$\tau(\text{RHO}) = \frac{-r\cos(\theta) + \sqrt{4r^2 - r^2\sin^2(\theta)}}{\nu} \tag{12}$$

if we assume that the relaying transmission range is equal to r and the MS's velocity is equal to ν. It is obvious that $\tau(\text{RHO})$ is determined for the extended transition range.

Let us assume that the handoff is initiated at time t_0. Then the dropping occurs if and only if the following conditions hold:

- The cellular system is in state N.
- The cellular system remains in state N for the next $\bar{t}$ seconds where $\bar{t} > \tau$.
- The call is not terminated in the next τ seconds.

If the cellular system is in the steady state, then the probability P_N of being in state N can be determined from the Markov chain of Figure 6:

$$P_N \frac{\frac{1}{N!}\left(\frac{\lambda+h}{\mu+h}\right)^N}{\sum_{i=0}^{N}\frac{1}{i!}\left(\frac{\lambda+h}{\mu+h}\right)^i} \tag{13}$$

When the cellular system is in state N, the state holding time is exponentially distributed with the parameter of $N(\mu + h)$. Assuming that the cellular system remains in state N for $\bar{t}$ seconds, we have:

$$P(\bar{t} > \tau) = \int_{\tau}^{\infty} N(\mu+h)e^{-N(\mu+h)t}dt = e^{-N(\mu+h)\tau} \tag{14}$$

Also, with the exponential call duration with parameter μ we have:

$$P(t > \tau) = e^{-\mu\tau} \tag{15}$$

where, t is the call duration and $P(t > \tau)$ is the probability that the call terminates after τ seconds from the handoff initiation. Therefore, the overall probability of a call being dropped is:

$$P_\tau(\text{drop}) = P_N \cdot P(\bar{t} > \tau) \cdot P(t > \tau) = \frac{\frac{1}{N!}\left(\frac{\lambda+h}{\mu+h}\right)^N}{\sum_{i=0}^{N}\frac{1}{i!}\left(\frac{\lambda+h}{\mu+h}\right)^i} e^{-(\mu+N(\mu+h))\tau} \tag{16}$$

The above dropping probability depends on τ which is a random number. Based on (12) the following equation holds for τ:

$$\tau(\nu,\theta) = \frac{-r\cos(\theta) + \sqrt{\sigma^2 - r^2\sin^2(\theta)}}{\nu} \tag{17}$$

Table 1. Initial parameter setting in Section 4

Parameter	Value
r	100.0 meters
Δ	10.0 meters
$1/\mu$	210.0 seconds
N	20 channels
$V_{\min}$	0.5 m/sec
$V_{\max}$	3.5 m/sec

where, $\sigma = r + \Delta$ for the LHO strategy and for the RHO strategy we use $\sigma = 2r$. Therefore, we have:

$$P(\text{drop}) = E(P_\tau(\text{drop})) = P_N \int_{V_{\min}}^{V_{\max}} \int_{-\pi/2}^{\pi/2} \frac{1}{\pi(V_{\max} - V_{\min})} e^{-(\mu+N(\mu+h))\tau(v,\theta)} d\theta dV \quad (18)$$

The double integral may be calculated numerically. In order to compare the LHO and RHO handoff models, the *dropping ratio* is defined as follows:

$$\text{Dropping Ratio} = \frac{P_{\text{LHO}}(\text{drop})}{P_{\text{RHO}}(\text{drop})} \quad (19)$$

It is clear that greater values of the dropping ratio are equal to smaller dropping probabilities in the RHO compared with the LHO. The value of the dropping ratio is independent of P_N.

Figures 7 to 11 illustrate how dropping ratio changes when different parameters of the system are changing. It is assumed that the parameter setting is as shown in Table 1. For each experiment, only one of these parameters is changing. It is obvious from these figures that the ad-hoc relaying may dramatically decrease the dropping probability. A number of simulations with the same set of assumptions, as mentioned in this section, are employed in order to test the analytical results. In Figures 7 to 11 the simulation results are compared with the analytical ones. It is clear from these figures that the analytical and simulation results are almost the same.

While the proposed analytical model illustrates how different parameters affect the behavior of the RHO, it is based on a number of assumptions which may not hold in different situations. In the next subsection we modify the derived analytical model by questioning the availability of the RS's.

4.2. Availability of Relay Stations

In the simple analytical model, proposed in the last subsection, it is assumed that the RS's are always available. In this subsection, it is shown that the availability of the RS's depends on the distance between the requesting MS and the corresponding AP. The analytical model is hence modified in order to include the RS-availability.

Let us assume that the distance between the MS and the AP is d and $d \geq r$. The potential relay stations for the MS are the ones inside the AP's coverage area and are at most r meters away from the MS. This is illustrated in Figure 12. Only the potential RS's, which are located inside the shaded zone, are available to be used by the MS. We call this zone as

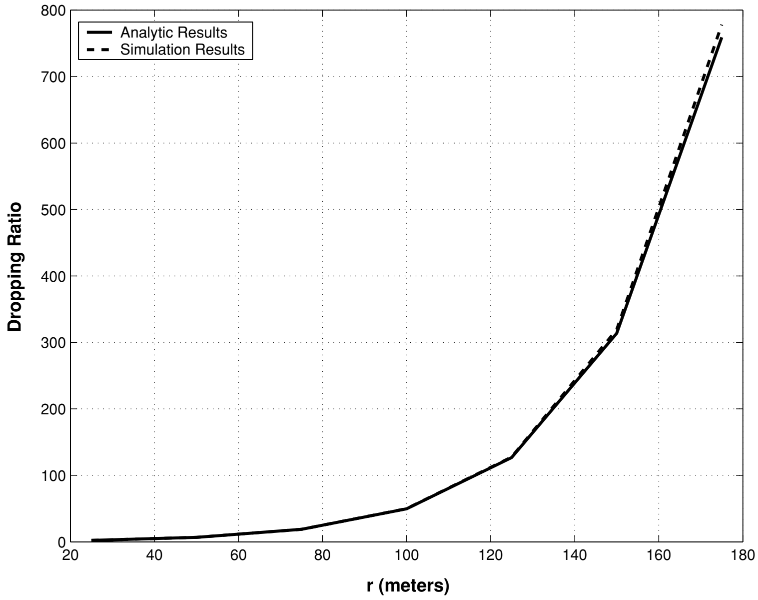


Figure 7. Dropping ratio when *r* is changing with respect to (18).

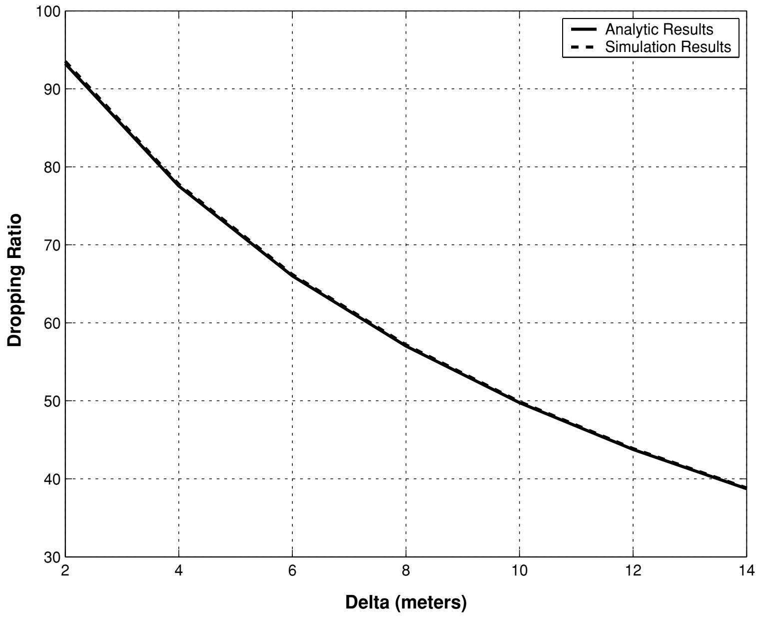


Figure 8. Dropping ratio when Δ is changing with respect to (18).

the *RS-availability region.* The location and the size of this region depend on the position of the MS with respect to the hotspot. The following definition states what we mean by the *probability of RS-availability*:

Definition **7** The probability of RS-Availability, when there are K potential RS's inside the hotspot is illustrated by $P_{\mathrm{RS}}^{\mathrm{K}}$ and is the probability of having at least one RS available to be used by the requesting MS.

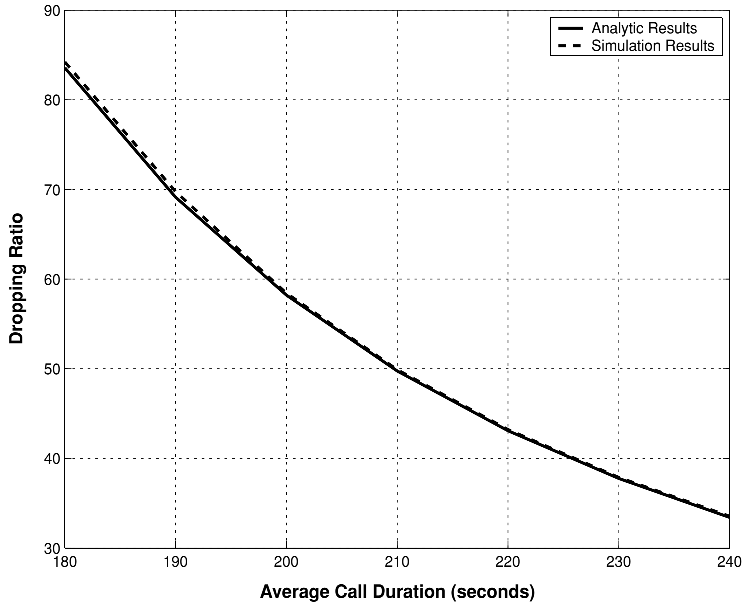


Figure 9. Dropping ratio when $1/\mu$ is changing with respect to (18).

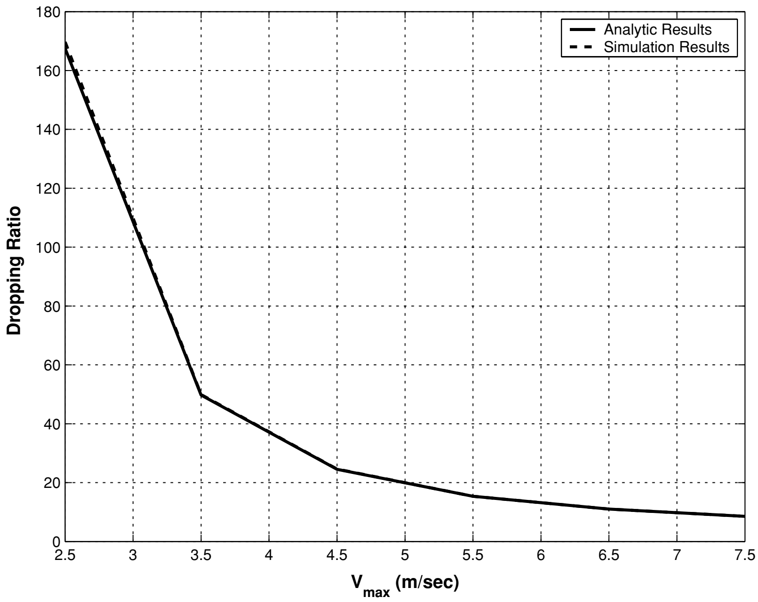


Figure 10. Dropping ratio when $V_{\max}$ is changing with respect to (18).

Based on Definition 7 and by the *uniform* distribution of nodes inside the hotspot's coverage area, we have:

$$P_{\mathrm{RS}}^{1} = \frac{\text{The area of the Rs availability region}}{\text{The area of the hotspot}} \tag{20}$$

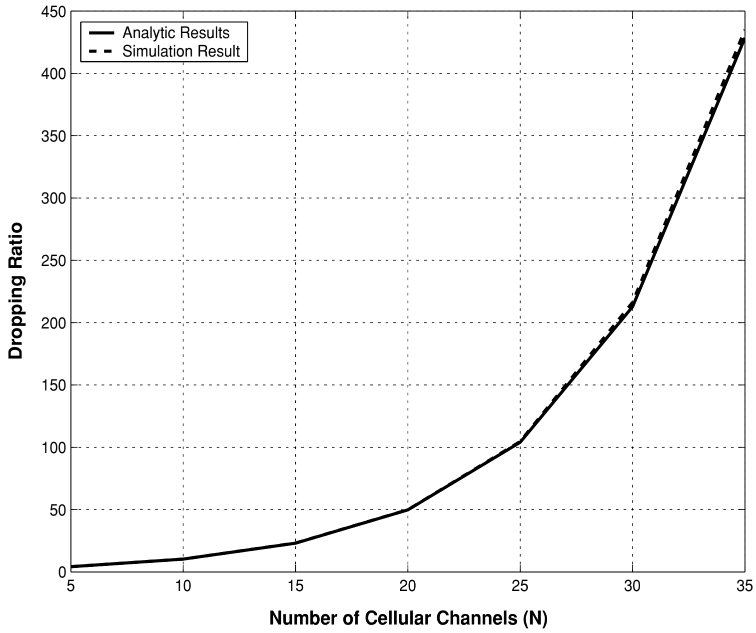


Figure 11. Dropping ratio when N is changing with respect to (18).

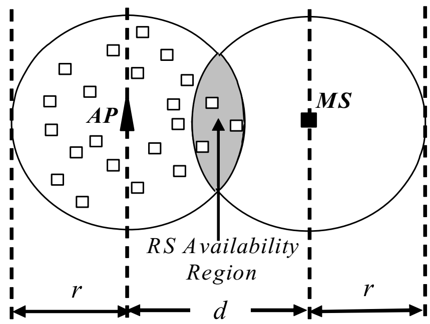


Figure 12. RS availability region. Only the potential RS's inside the shaded region may be used by the MS.

It can be shown that:

$$P_{\mathrm{RS}}^{1}(d,r) = \frac{2r^2\cos^{-1}\left(\frac{d}{2r}\right) - d\sqrt{r^2 - d^2/4}}{\pi r^2} \tag{21}$$

We define Ψ as the following:

$$\Psi \hat{=} \frac{d}{r} \tag{22}$$

Based on (21) and (22) we have:

$$P_{\mathrm{RS}}^{1}(\Psi) = \frac{2}{\pi}\cos^{-1}\left(\frac{1}{2}\Psi\right) - \frac{1}{\pi}\Psi\sqrt{1 - \frac{1}{4}\Psi^2} \tag{23}$$

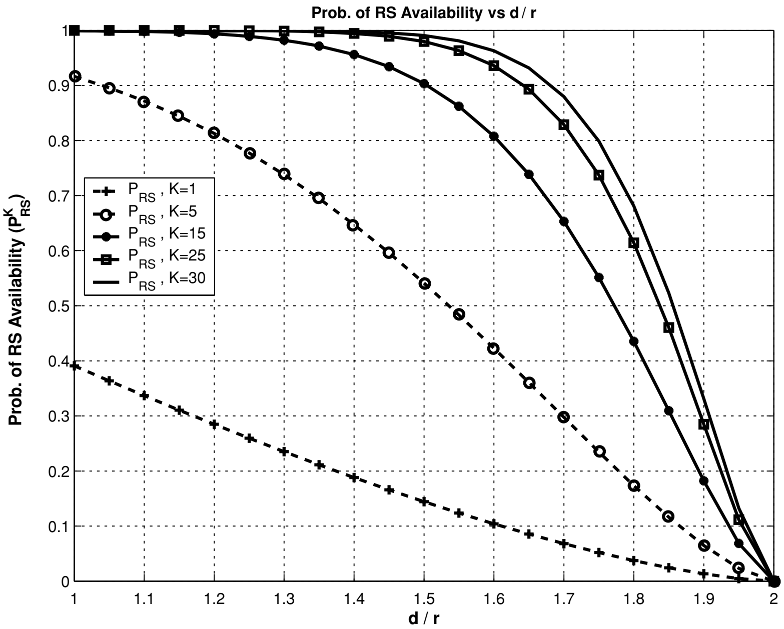


Figure 13. Probability of RS availability when $\Psi = d|r$ is changing.

Therefore, with K potential relay stations the following holds:

$$P^K_{\mathrm{RS}}(\Psi) = 1 - \left(1 - P^1_{\mathrm{RS}}(\Psi)\right)^K \tag{24}$$

Figures 13 and 14 illustrate how $P^K_{\mathrm{RS}}(\Psi)$ changes when K and Ψ are changing. As it is expected, if $d \to 2r$ then $P^K_{\mathrm{RS}} \to 0$. With reduction of d we observe a significant increase in P^K_{RS}. For example, when $d = 1.5r$ we have $\Psi = 1.5$ and it is clear from Figure 14 that $P^5_{\mathrm{RS}}(1.5) > 0.5$. The simulation results are compared in Figure 15 with the analytical ones which are determined based on (24).

In the previous subsection we assumed that at least one RS is available for every active MS in the relaying mode. This assumption holds only when $P^K_{\mathrm{RS}} \to 1$. In order to modify the analysis of the previous subsection, $P^K_{\mathrm{RS}}(\Psi)$ must be included in the model. However, taking $P^K_{\mathrm{RS}}(\Psi)$ into account, makes the model too complex. Therefore, we estimate $P^K_{\mathrm{RS}}(\Psi)$ by the following function:

$$\tilde{P}^K_{\mathrm{RS}}(\Psi) = \begin{cases} 1 & \text{if } \Psi \leq \xi \\ 0 & \text{if } \Psi > \xi \end{cases} \tag{25}$$

where ξ is a threshold value. The value of ξ is selected such that the following equation holds:

$$\int_{1.0}^{2.0} P^K_{\mathrm{RS}}(\Psi)\, d\Psi = \int_{1.0}^{2.0} \tilde{P}^K_{\mathrm{RS}}(\Psi)\, d\Psi = \xi - 1 \tag{26}$$

This estimation is same as assuming that the RS's are always available when the distance

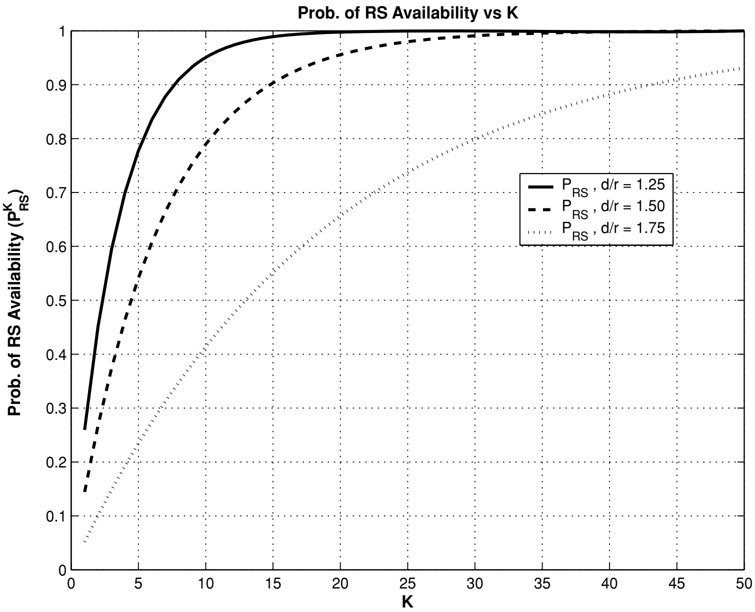


Figure 14. Probability of RS availability when K is changing.

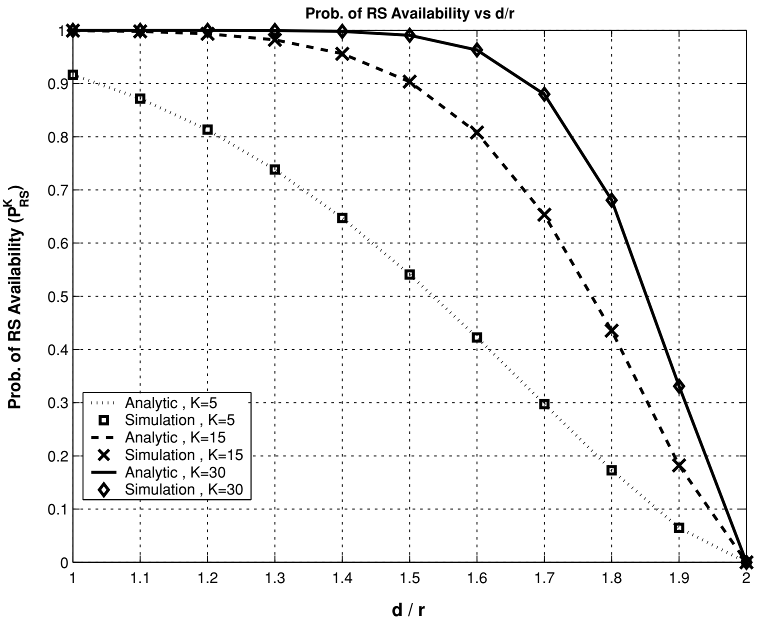


Figure 15. Probability of RS availability. Comparison between simulation and analytical model.

between the AP and the MS is less than $r\xi$, where:

$$\xi = 1 + \int_{1.0}^{2.0} P_{\mathrm{RS}}^{K}(\Psi)\, d\Psi \tag{27}$$

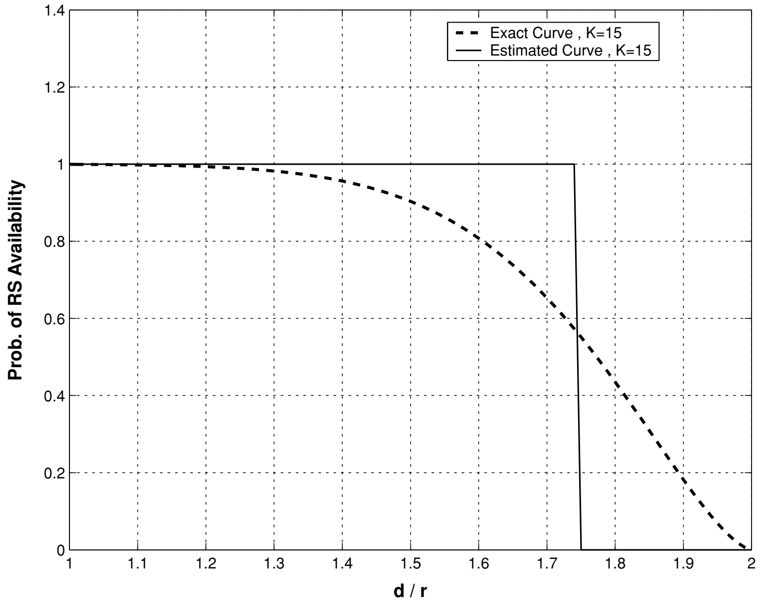


Figure 16. Probability of RS availability. Comparison between exact and estimated functions for $K = 15$.

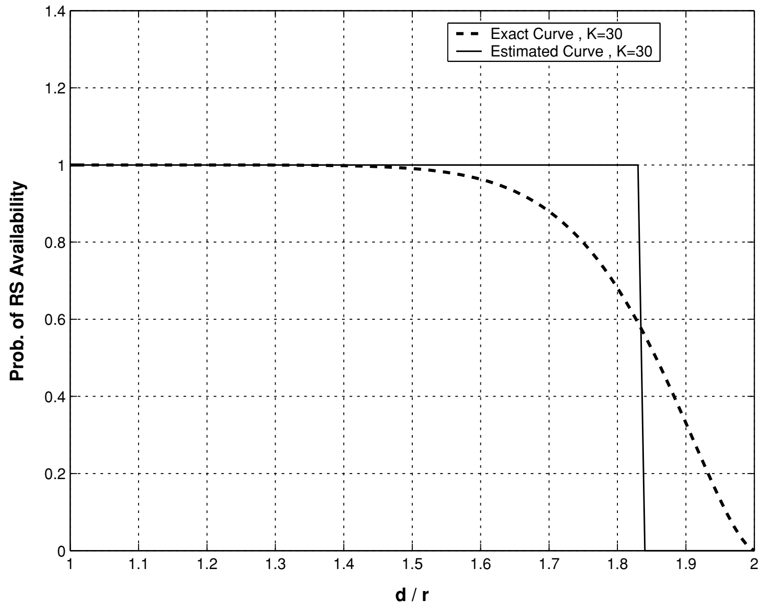


Figure 17. Probability of RS availability. Comparison between exact and estimated functions for $K = 30$.

Figures 16 and 17 show how $\tilde{P}^K_{\mathrm{RS}}(\Psi)$ changes with respect to Ψ and it is compared with the exact value of $P^K_{\mathrm{RS}}(\Psi)$. As it is defined by (26), the area under $\tilde{P}^K_{\mathrm{RS}}(\Psi)$ curve and the original function, $P^K_{\mathrm{RS}}(\Psi)$, are equal, Using $\tilde{P}^K_{\mathrm{RS}}(\Psi)$ the dropping probability of the RHO strategy, as

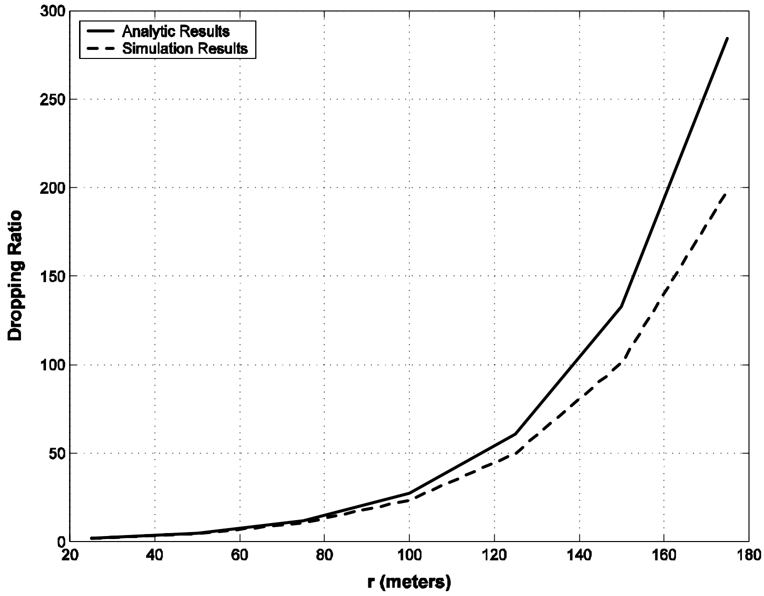


Figure 18. Dropping ratio when r is changing with respect to (28).

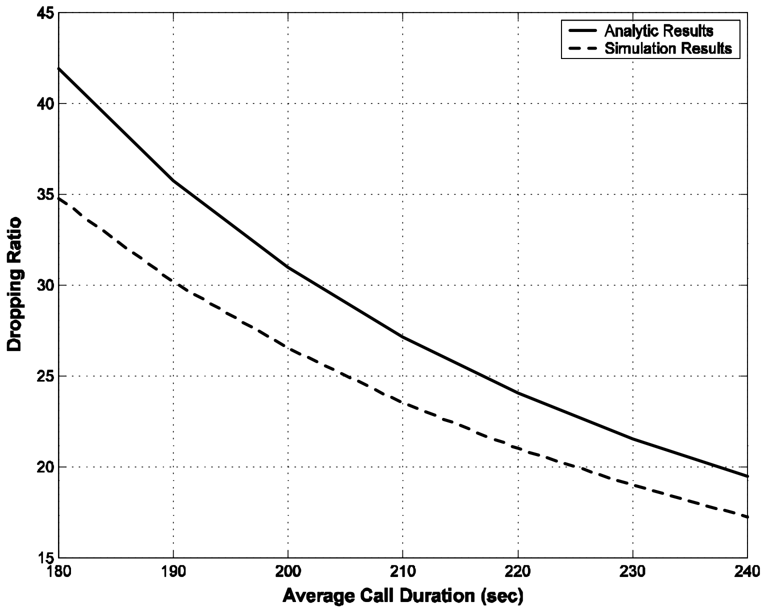


Figure 19. Dropping ratio when $1/\mu$ is changing with respect to (28).

described by (18), may be modified in the following manner:

$$P(\text{drop}) = P_N \int_{V_{\min}}^{V_{\max}} \int_{-\pi/2}^{\pi/2} \frac{1}{\pi(V_{\max} - V_{\min})} e^{-(\mu+N(\mu+h))\frac{-r\cos(\theta)+\sqrt{(r\xi)^2-r^2\sin^2(\theta)}}{V}} d\theta dV \tag{28}$$

The results of the above analytical model are compared with the simulation results in Figures 18 to 21. The parameter setting is similar to Table 1. The simulation environment is

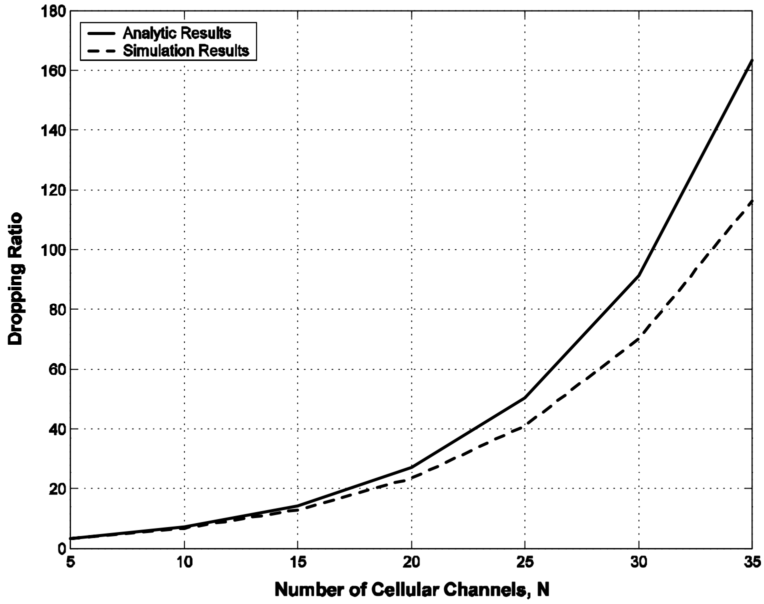


Figure 20. Dropping ratio when *N* is changing with respect to (28).

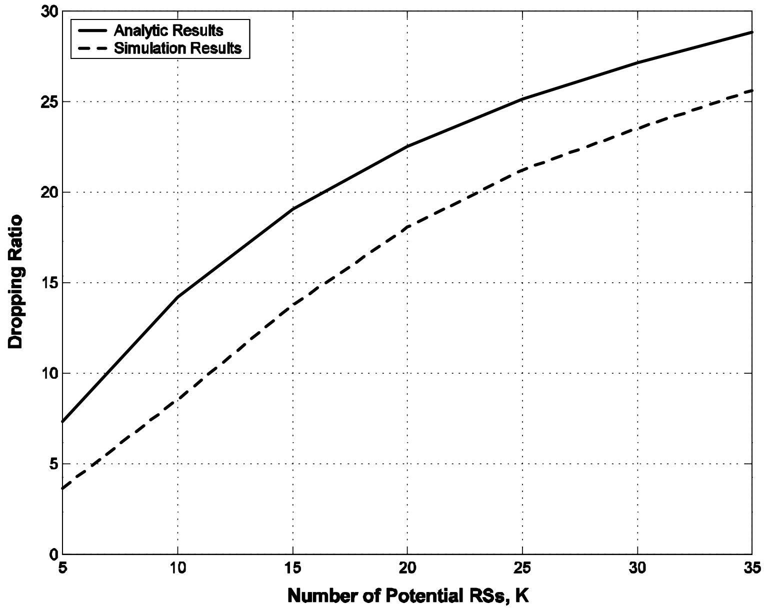


Figure 21. Dropping ratio when *K* is changing with respect to (28).

based on the assumptions consistent with the analytical model. It is clear from these figures that the simulation results are to some extend different from the analytical ones. This difference is expected because of the estimation which is made by (25). However, both simulation and analytic results show that the RHO reduces the dropping rate dramatically compared with the non-relaying situation.

Different system-parameters are examined in Figures 7 to 11 and 18 to 21. An increase in each parameter may have a certain effect on the performance of the proposed RHO. When the mobile stations are moving faster, they leave the original and extended transition areas more rapidly and they have a lower chance of successful handoff. Increasing the average call duration decreases the defined dropping ratio. It is clear that if the call duration is going to be long enough, the call will eventually be dropped. When the number of potential RS's is increased, the probability of RS availability increases too. Therefore, with the RHO, the dropping probability is decreased. Furthermore, with a greater number of channels in the cellular system, when the cellular system is in state N, the state holding time becomes shorter and hence, lower dropping probabilities are expected.

5. Simulation Results

In the previous section the RHO method is compared with the LHO through simple analytical modeling. In this section these methods are compared through simulations. A large number of simulations have been performed to evaluate the performance of the proposed method. In the following, we will only describe some of the more important results. The mobility model, which is introduced in the following, is a modified version of the well-known *random waypoint* mobility model [31].

An event-based simulator is developed to evaluate the performance of the proposed methods. It is assumed that there is only one cell and one WLAN, as two circles, and the WLAN is located inside the cell. The hotspot and cell radii are assumed to be 100 and 1000 meters respectively.

The MS's are classified as either *Inside* or *Outside* ones, depending on their locations respect to the hotspot. For each class of MS's a *random way point* mobility model is used. Each MS moves from its current position toward its random destination with a random velocity. The destination of an Inside MS is selected outside the hotspot with a probability of 0.35 while the destination of an Outside MS is selected inside with a probability of 0.1. Inside MS's velocity has a uniform distribution between 0.5 and 2.0 m/sec while the velocity of the Outside MS's is uniformly distributed between 1.0 and 15.0 m/sec. When an Inside MS arrives at its destination, it waits there for a random time uniformly distributed between 0.0 and 300.0 seconds. There are 1000 of MS's and with this parameter setting, when the system is in steady state, about 325 of MS's are inside the hotspot. Figure 22 shows the distribution of MS's over the simulation area. Figure 23 illustrates how the system reaches stability.

New call generation rate is 0.3 calls/sec and new calls are generated based on a Poisson distribution. Call duration is an exponentially distributed random variable. The average call duration is a simulation parameter and is selected between 180 to 240 s. It is assumed that the hotspot (WLAN) can serve 36 connections. Also it is assumed that the cellular system has 56 channels. Initial parameter setting which is used in the simulations is illustrated in Table 2. Some of these parameters were used as variables in the simulations.

When an Inside (Outside) MS with an active connection moves outside (inside) the hotspot a handoff is initialized. Rejected handoff requests are en-queued in order to wait for a free channel. It is assumed that even Inside MS's can be served by the cellular system. Therefore, there is no dropping event when a Cellular-to-WLAN handoff is being rejected.

Let us see what will happen when a WLAN-to-Cellular handoff is rejected. In the LHO model, these rejected requests are en-queued. In this case, when the distance between the MS and the AP is more than an upper bound, $r + \Delta$, the connection is dropped. In the RHO model,

Table 2. Initial parameter setting in Section 5

Parameter	Definition	Value
r	Hotspot radius	100.0 meters
ρ	Relaying transmission range	100.0 meters
A	Original transition area's width	10.0 meters
$1/\mu$	Average call duration	210.0 seconds
N	Number of cellular channels	56 channels
M	Maximum number of connections served by the hotspot	36 active calls
$\lfloor V^I_{\min}, V^I_{\max} \rfloor$	The velocity of inside MS's is uniformly distributed over this range	[0.5, 2.0] m/sec
$\lfloor V^O_{\min}, V^O_{\max} \rfloor$	The velocity of outside MS's is uniformly distributed over this range	[1.0, 15.0] m/sec
T_{pause}	Inside MS's waits at their destinations for a random time uniformly distributed over [0, T_{pause}]	300.0 seconds

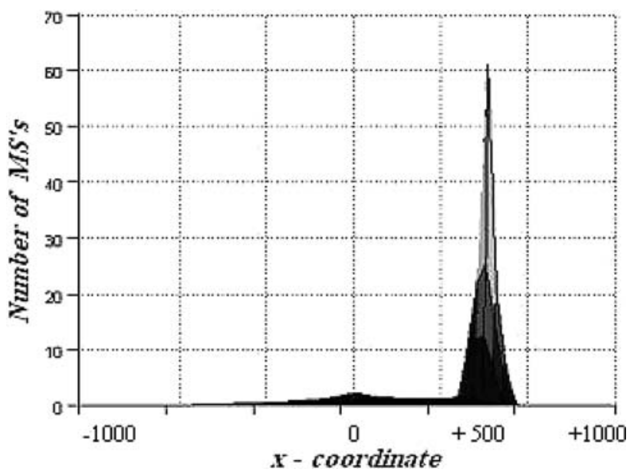


Figure 22. Distribution of MS's on the simulation area.

when the rejected request is en-queued, the MS finds an RS and through ad hoc relaying stays connected with its original AP. The call is dropped when there is no free channel in the cell and there is no relaying path available as well as the distance between the MS and the AP is greater than $r + \Delta$. En-queued handoff requests are served in a *first come first serve* manner when at least one free channel is available in the cellular side.

Different metrics could be used in order to select an RS, among a number of candidates. Link quality on the MS-RS and RS-AP connections can be used as a parameter for choosing an RS in the RHO model. Other parameters such as remaining battery power, power consumption, fairness and path stability can be considered too. When certain QoS requirements exist, RS selection may be performed with respect to a number of constraints [32].

In the RHO model, each MS that is served by the WLAN is connected to the AP through one or two hop wireless links. Therefore, number of hops in the relaying path, is not an appropriate metric for the RS selection. In this paper, we choose the RS based on the method described in [22]. Therefore, assuming that S is the set of potential RS's, any of the following equations

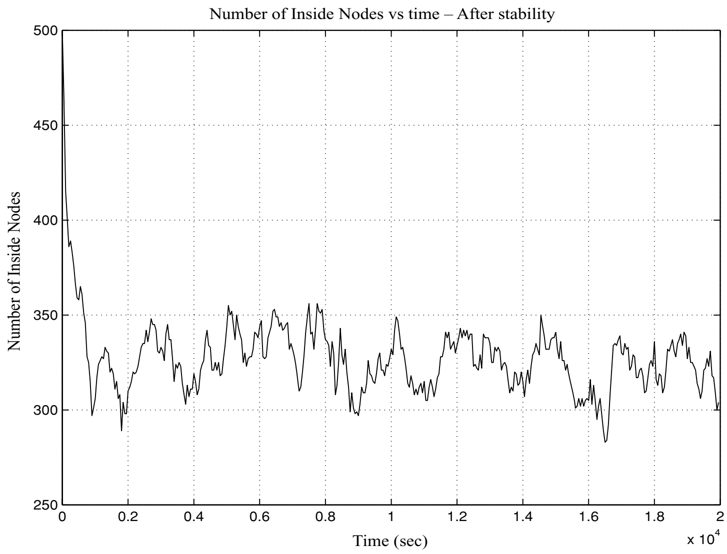


Figure 23. Stability in the number of nodes inside the hotspot.

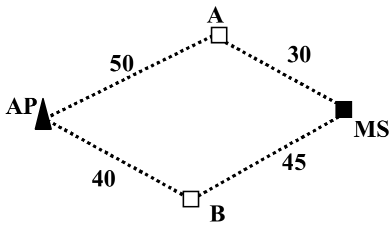


Figure 24. Example of selecting an RS in RHO; node *B* is selected.

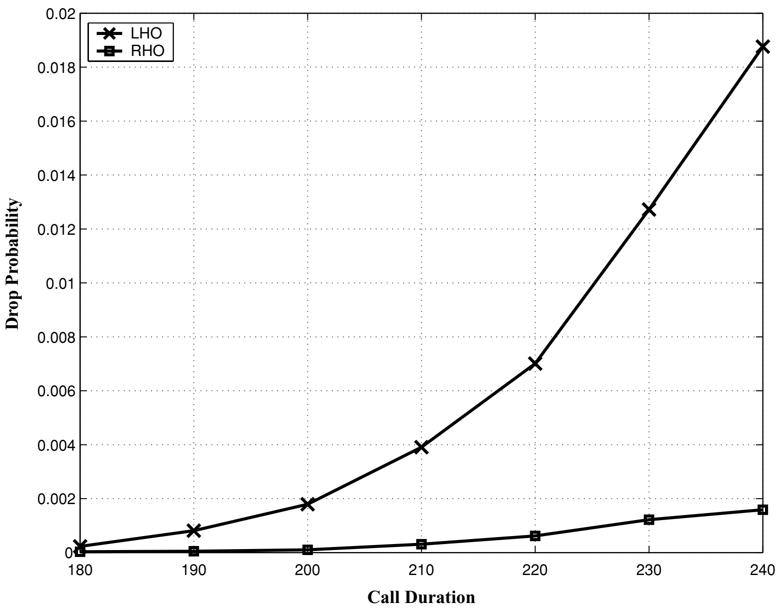


Figure 25. Dropping probability vs. average call duration.

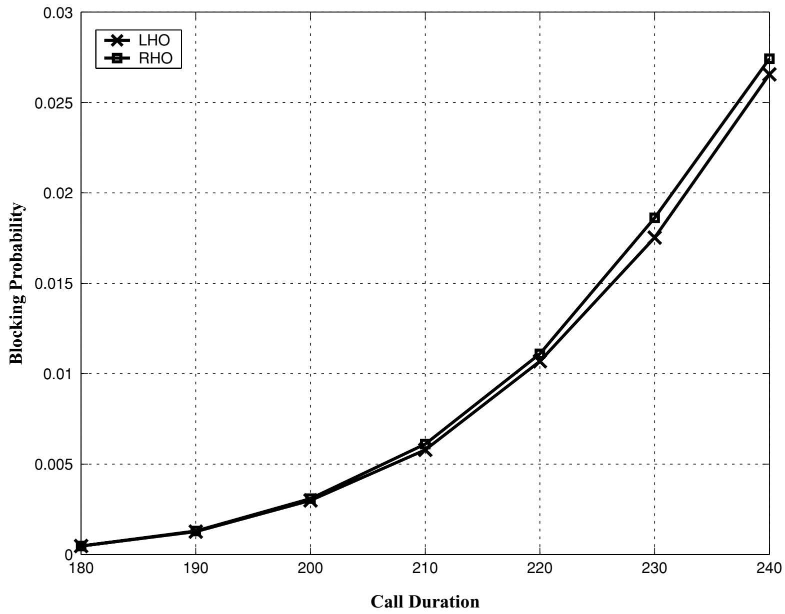


Figure 26. Blocking probability vs. average call duration.

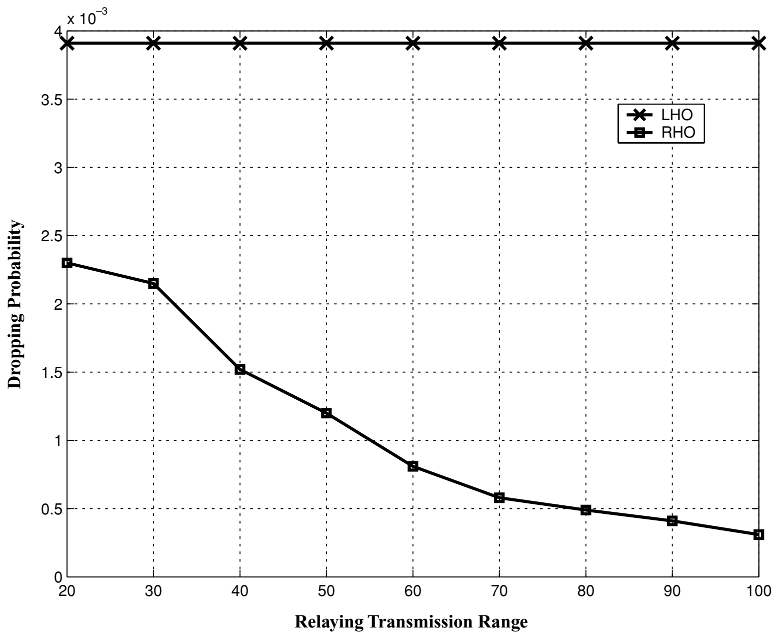


Figure 27. Dropping probability vs. relaying transmission range.

can be used in order to select an RS:

$$\text{RS} = \arg\min_{\text{RS}_i \in S} \max(\text{dist}(\text{MS}, \text{RS}_i), \text{dist}(\text{RS}_i, \text{AP})) \tag{29}$$

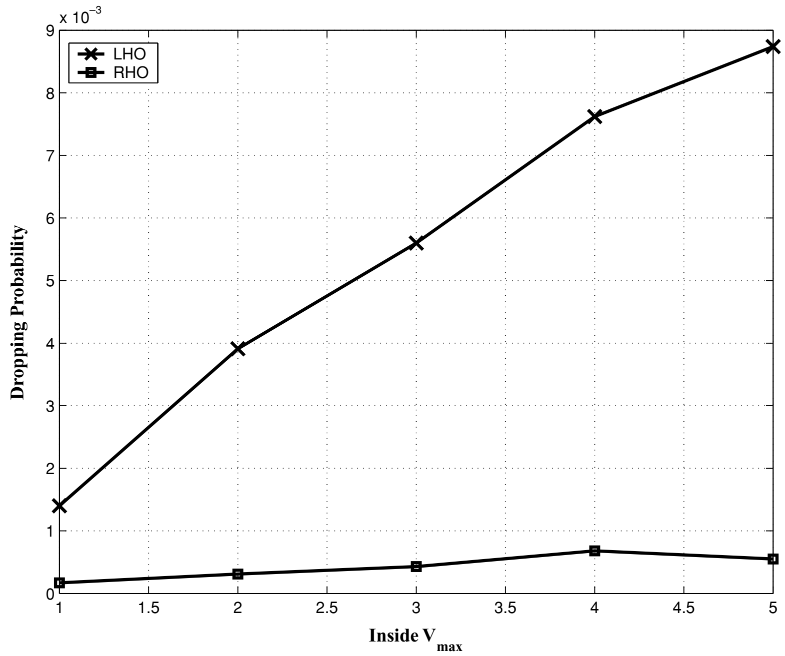


Figure 28. Dropping probability vs. maximum inside velocity.

and/or

$$\mathrm{RS} = \arg \min_{\mathrm{RS}_i \in S} \max(\mathrm{PL}(\mathrm{MS}, \mathrm{RS}_i), \mathrm{PL}(\mathrm{RS}_i, \mathrm{AP})) \tag{30}$$

where, RS is the selected relay station and RS_i is the ith potential relay station. Also, dist(X, Y) and PL(X, Y) are the distance and path loss between nodes X and Y respectively. An example is illustrated in Figure 24, where two relay stations are available. Based on (29), relay station B is selected, because the longest link of path MS-B-AP is 45 meters while the longest link of MS-A-AP is 50.

Simulation results are shown in Figures 25 to 28. Figure 25 illustrates the dropping probability when the average call duration is changing from 180 to 240 s. Blocking probabilities for the same parameters are shown in Figure 26. The proposed relaying method reduces the dropping probability with almost no change in the blocking probability.

Figure 27 illustrates the dropping probability when the relaying transmission range is changing from 20 meters to 100 meters. It is obvious from this figure that when the relaying transmission range is reduced the dropping probability of the RHO strategy converges toward that of the LHO. This is expected because the extended transition range shrinks. Figure 28 shows the dropping probability when the maximum velocity of inside nodes is changing from 1.0 to 5.0 m/sec. As it is clear from these figures, the RHO has much lower dropping probability compared to the LHO method.

Overall the simulation results prove that the proposed RHO method is superior to the traditional handoff strategies in terms of reducing the dropping probability.

6. Conclusions

In this paper, we suggested the use of the ad hoc relaying for reducing the dropping rate in a hybrid WLAN/cellular system. Dropping probability reduction by traditional methods such as using reserved guard channels is not an easy task in loosely coupled hybrid systems. The dropping probability can dip down to an acceptable value when the proposed RHO strategy is employed. Both analytical reasoning and simulation results show the effectiveness of the suggested strategy. Simple analytical models are proposed in this paper to evaluate the performance of the proposed RHO method. While we proposed and evaluated the relaying method for a hybrid WLAN/Cellular system, it can also be used in other applications. These applications could include tightly coupled hybrid networks or traditional single layer cellular systems where the ad hoc relaying reduces the need for channel reservation.

References

1. IEEE Standards Department, *IEEE Draft Standard - Wireless LAN*, IEEE Press, 1996.
2. A. Doufexi, et al., "Hotspot Wireless LANs to Enhance the Performance of 3G and Beyond Cellular Networks", *IEEE Communications Mag.*, pp. 58–65, July 2003.
3. K. Ahmavaara, H. Haverinen, and R. Pichna, "Interworking Architecture Between 3GPP and WLAN Systems", *IEEE Communications Magazine*, pp. 74–81, Nov. 2003.
4. Q. Zhang, et al., "Efficient Mobility Management for Vertical Handoff Between WWAN and WLAN", *IEEE Comm. Mag.*, pp. 102–108, Nov. 2003.
5. R. Fantacci, "Performance Evaluation of Prioritized Handoff Schemes in Mobile Cellular Networks", *IEEE Trans. On Vehicular Technology*, Vol. 49, No. 2, pp. 485–493, 2000.
6. J. Misic and T.Y. Bun, "About the Problem of Hot-Spots Under Adaptive Admission Control in Wireless Multimedia Networks", *Proceedings of IEEE WCNC*, pp. 1238–1242, 1999.
7. S. De, O. Tonguz, H. Wu, and C. Qiao, "Integrated Cellular and Ad Hoc Relay (iCAR) Systems: Pushing the Performance Limits of Conventional Wireless Networks", *Proceedings of HICSS*, pp. 3899–3906, 2002.
8. T. Todd and D. Zhao, "Cellular CDMA Capacity in Hotspots with Limited Ad hoc Relaying", *Proceedings of IEEE PIMRC*, 2003.
9. J.H. Yap. X. Yang et al., "Position Assisted Relaying and Handover in Hybrid Ad hoc WCDMA Cellular Systems", *Proceedings of IEEE PIMRC*, pp. 2194–2198, Sept. 2002.
10. G.N. Aggelou and R. Tafazolli, "On the Relaying Capability of Next-Generation GSM Cellular Networks", *Proceedings of IEEE Personal Communications*, pp. 40–47, Feb. 2001.
11. T. Rouse, S. McLaughlin, and H. Haas, "Coverage-Capacity Analysis of Opportunity Driven Multiple Access (ODMA) in UTRA TDD", *Proceedings of the International Conf. on 3G Mobile Communication Technologies*, pp. 252–256, 2001.
12. M. He, T.D. Todd, D. Zhao, and V. Kezys, "Ad Hoc Assisted Handoff for Real-Time IEEE 802.11 Infrastructure WLANs", *Proceedings of the IEEE WCNC*, 2004.
13. M. Rahnema, "Overview of the GSM System and Protocol Architecture", *IEEE Communications Magazine*, April 1993.
14. J. Cai and D.J. Goodman, "General Packet Radio Service in GSM", *IEEE Communications Magazine*, pp. 122–131, Oct. 1997.
15. J. Korhonen, *Introduction to 3G Mobile Communications*, Artech House, 2nd Edition, 2003.
16. D.B. Johnson and D.A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks", In Tomasz Imielinski and Hank Korth *Mobile Computing*, eds., Kluwer Academic Publishers, Chap 5, p. 153–181, 1996.
17. C.E. Perkins and E.M. Royer, "Ad hoc On-Demand Distance Vector Routing", *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, New Orleans, LA, pp. 90–100, February 1999.
18. R. Ramanathan and J. Redi, "A Brief Overview of Ad Hoc Networks: Challenges and Directions", *IEEE Communications Magazine*, pp. 20–22, May 2002.
19. Y.D. Lin and Y.C. Hsu, "Multihop Cellular: A New Architecture for Wireless Communications", *Proceedings*

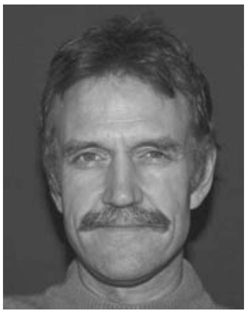
of Infocomm, pp. 1273–1282, 2000.
20. H.C. Chao and C.Y. Huang, “Micro-Mobility Mechanism for Smooth Handoffs in an Integrated Ad-Hoc and Cellular IPv6 Network Under High-Speed Movement”, *IEEE Trans. on Vehicular Technology*, Vol. 52, No. 6, pp.l576–1593, 2003.
21. D. Zhao, and T.D. Todd, “Real-Time Traffic Support in Relayed Wireless Access Networks Using IEEE 802.11”, *IEEE Wireless Communications*, pp. 32–39, April 2004.
22. V. Sreng, H. Yanikomeroglu, and D.D. Falconer, “Relayer Selection Strategies in Cellular Networks with Peer–to-Peer Relaying”, *Proceedings of the IEEE VTC'F03*, Oct. 2003.
23. J.W. Florolu, et al., “Seamless Handover in Trestrial Radio Access Networks: A Case Study”, *IEEE Comm. Mag.*, pp. 110–116, Nov. 2003.
24. K. Pahlavan and P. Krishnamurthy, et al., “Handoff in Hybrid Mobile Data Networks”, *IEEE Personal Communications*, pp. 34–47, April 2000.
25. M. Portoles, et al., “IEEE 802.11 Link-Layer Forwarding for Smooth Handoff”, *Proceedings of IEEE PIMRC*, pp. 1420–1424, 2003.
26. Y. Pan, et al., “An End-to-End Multipath Smooth Handoff Scheme foe Stream Media”, *IEEE JSAC*, May 2004.
27. D. Tandjaoui, et al., “Performance Enhancement of Smooth Handoff in Mobile IP by Reducing Packets Disorder”, *Proceedings of IEEE ISCC*, 2003.
28. P. Khadivi, T.D. Todd, and D. Zhao, “Handoff Trigger Nodes for Hybrid IEEE 802.11 WLAN/Cellular Networks”, *Proceedings of the First International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (Qshine 2004)*, Dallas, USA, pp. 164–170, 2004.
29. P. Khadivi, T.D.Todd, S. Samavi, H. Saidi, and D. Zhao, “Mobile Ad Hoc Relaying in Hybrid WLAN/Cellular Systems for Dropping Probability Reduction”, *Proceedings of the 9th CDMA International Conference (CiC 2004)*, Korea, 25–28, Oct. 2004.
30. D. Hong and S.S. Rappaport, “Traffic Model and Performance Analysis for Cellular Mobile Radio Telephone Systems with Prioritized and Nonprioritized Handoff Procedures”, *IEEE Trans. on Vehicular Technology*, Vol. 35, No. 3, pp.. 448–461, Aug. 1986.
31. C. Bettstetter and C. Wagner, “The Spatial Node Distribution of the Random Waypoint Mobility Model”, *Proceedings of WMAN*, pp. 41–58, 2002.
32. P. Khadivi, S. Samavi, T.D. Todd, and H. Saidi, “Multi-Constraint QoS Routing Using a New Single Mixed Metric”, *Proceedings of IEEE International Conference on Communications (ICC 2004)*, Vol. 4, 20–24 June Paris, France, pp. 2042–2046, 2004.

Pejman Khadivi received the BS and MS degrees in computer engineering (Hardware and Computer Systems Architecture) in 1998 and 2000, respectively from Isfahan University of Technology, where he is currently working toward his Ph.D. During the 2003/2004 academic year, he was a Visiting Researcher with the Electrical and Computer Engineering Department, McMaster University, ON, Canada. Different aspects of computer architecture and networking are Mr. Khadivi's research interests specially, adhoc networks, QoS routing and seamless handoff in hybrid mobile networks.

Shadrokh Samavi received the B.S. degrees in industrial technology and electrical engineering from the California State University, Fresno, in 1980 and 1982, respectively, the M.S. degree from the University of Memphis, Memphis, TN, in 1985, and the Ph.D. degree in electrical engineering from Mississippi State University, Mississippi State, in 1989. In 1995, he joined the Electrical and Computer Engineering Department, Isfahan University of Technology, Isfahan, Iran, where he was an Associative Professor. During the 2002/2003 academic year, he was a Visiting Professor with the Electrical and Computer Engineering Department, McMaster University, Hamilton, ON, Canada. His current research interests are implementation and optimization of image-processing algorithms and area-performance tradeoffs in computational circuits. Dr. Samavi is a Registered Professional Engineer (P.E.), USA, and is a member of Eta Kappa Nu, Tau Beta Pi, and the National Association of Industrial Technologists (NAIT).

Hossein Saidi received the B.S. and M.S. degrees in electrical engineering (Electronics and communication Eng.) from Isfahan University of Technology (IUT), in 1986 and 1989, respectively, and the Ph.D. degree in electrical engineering from the Washington University in St. Louis, MO. in 1994.

From 1994 to 1995, he was a research associates at Washington Univ. St. Louis, and in 1995 he joined the Electrical and Computer Engineering of IUT, where he is an Associate Professor. His Research interest includes ATM, high speed networking, QoS guarantees, routing, algorithms and information theory.



Terence D. Todd received the B.A.Sc, M.A.Sc and Ph.D degrees in Electrical Engineering from the University of Waterloo, Waterloo, Ontario, Canada. While at Waterloo he spent 3 years as a Research Associate with the Computer Communications Networks Group (CCNG). He is currently a Professor of Electrical and Computer Engineering at McMaster University in Hamilton, Ontario, Canada.

Professor Todd spent 1991 on research leave in the Distributed Systems Research Department at AT&T Bell Laboratories in Murray Hill, NJ. He also spent 1998 on research leave at The Olivetti and Oracle Research Laboratory in Cambridge, England. While at ORL he worked on the piconet project which was an early embedded wireless network testbed.

Dr. Todd's research interests include metropolitan/local area networks, wireless communications and the performance analysis of computer communication networks and systems. He currently holds the NSERC/RIM/CITO Industrial Research Chair on Pico-Cellular Wireless Internet Access Networks. Dr. Todd is a Professional Engineer in the province of Ontario and a member of the IEEE.

Dongmei Zhao received the Ph.D degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, Ontario, Canada in June 2002. Since July 2002 she has been with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada where she is an assistant professor. Dr. Zhao's research interests include modeling and performance analysis, quality-of-service provisioning, access control and admission control in wireless cellular networks and integrated cellular and ad hoc networks. Dr. Zhao is a member of the IEEE.