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Hand-Off Performance of the Integrated Cellular and Ad Hoc Relaying (iCAR) System *

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Abstract. In this paper, we study the hand-off performance of a wireless system with heterogeneous technologies called *iCAR (Integrated Cellular and Ad hoc Relaying)*. In iCAR, hand-offs can occur not only from a Base Transceiver Station (BTS) to another BTS, but also from a BTS to a so-called *Ad hoc Relaying Station (ARS)* in the form of relaying, as well as from an ARS back to a BTS. The latter two types of hand-offs effectively increase the hand-off buffer time and thus reduce the call dropping probability. We develop an analytical model for the hand-off performance in iCAR. In addition, we verify the analytical model via simulations and quantify the hand-off performance benefits of the iCAR system over conventional cellular systems. It is anticipated that the analytical and simulation models reported in this paper will serve as a guideline to other researches on the inter-system hand-off involving heterogenous wireless technologies.

Keywords: iCAR, ad hoc relaying, cellular networks, hand-off performance evaluation

1. Introduction

In cellular concept [16], a geographical area is divided into small units called *cells*, each having a Base Transceiver Station (BTS). A portion of the total pool of channels are allocated to each of these BTS's, and the adjacent cells use different sets of channels to minimize the co-channel interference. Hence, a call in progress needs to be handed over to a neighboring cell, while the Mobile Host (MH) moves across cells. Hand-off of a call is important in the sense that dropping of an on-going call is more annoying to the subscriber than blocking of a new call. One way of reducing the dropping probability of a hand-off call is to reserve a fixed number of channels (called guard channels) exclusively for the hand-off requests [15]. However, this may reduce the channel efficiency [11].

In addition to the cellular networks, various wireless technologies and systems (such as Satellite Systems [12], Wireless Local Area Networks (WLANs) [3], Mobile Ad hoc Networks (MANET) [5,17], Bluetooth [13], Home RF Networks [18], and Sensor Networks [1,23]) have been developed over the years. The emergence of different wireless technologies have called for the need of an integrated heterogeneous wireless infrastructure, to make the communication system more efficient and robust. In [29], the *integrated Cellular and Ad hoc Relaying* (*iCAR*) system was introduced to address the congestion problem due to limited bandwidth in a cellular system and provide interoperability in heterogeneous networks. In iCAR, an MH is allowed to use the Data Channel (DCH) available in a nearby cell (other than the cell it is located in) via relaying through *Ad hoc Relaying Stations* (*ARS's*) which are placed at strategic locations in the system. By using ARS's along with the signaling and routing protocols presented in [27], it is possible to divert traffic from one (possibly congested) cell to another (non-congested) cell. This helps circumvent congestion, and makes it possible to maintain (or hand-off) connections involving MH's that are moving into a congested cell, or to accept new call requests involving MH's that are in a congested cell.

In [28,29], the performance of iCAR in terms of the call blocking probability was studied via analysis and simulations. It was shown that iCAR could effectively balance traffic load among cells, and more importantly, overcome the barriers imposed by the cell boundaries and share channels between cells, which in turn leads to significantly lower call blocking probability than a corresponding cellular system. Note that,

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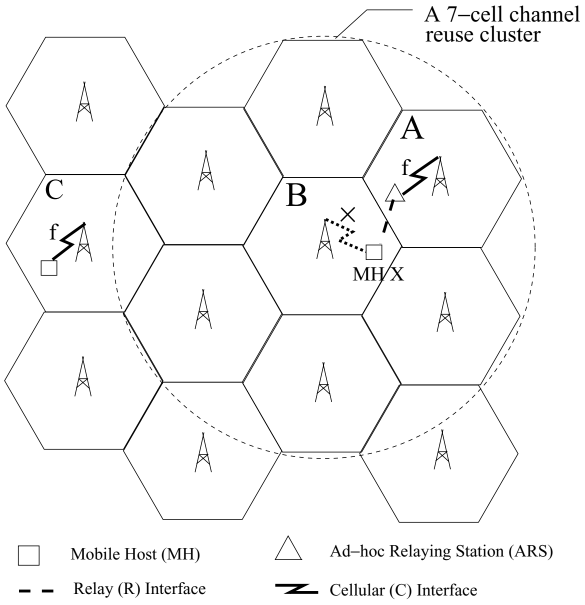

Figure 1. iCAR has a better channel efficiency than DCA or channel borrowing does.

although dynamic channel assignment (DCA) approach [4,24] can assign the channels to the cells dynamically as calls arrive, and the channel borrowing approach [6] can borrow available channels from neighboring cells when congestion occurs,[1] their performance is still limited by the co-channel interference constraint. More specifically, in order for two cells to use the same channels without co-channel interference, the two cells have to be at least d cells apart from each other (where d is normally equal to 2). As can be seen from figure 1, if channel f is used by an MH in cell C which is only $d-1$ cells apart from cell B, then the MH X in cell B cannot use channel f. However, in iCAR (see Section 2 for the operations of iCAR), the MH X can use channel f through relaying to achieve a better performance as long as f is available in the neighboring cell A (which is d cells apart from cell C). Note that, relaying may also be affected by the channel interference within the relaying spectrum itself. However, such interferences can be minimized using a special medium access control (MAC) protocol, such as signature laced communication, or use of smart antennas [19]. However, we do not address the interference and MAC issues in this paper.

In this paper, we focus on the hand-off performance in an iCAR system, and compare the hand-off call dropping probability of iCAR with that of the conventional cellular system using fixed channel assignment (FCA) approach. The analytical model for hand-off performance is generated through a number of steps which include the derivation of the distribution function of the hand-off buffer time, the probability that a hand-off request will be blocked in iCAR, and the derivation of the probability that a hand-off request occurs. In addition, we conduct simulation experiments with more realistic assumptions to verify our analysis and quantify the hand-off performance gain in the iCAR system. For a fair comparison, it is assumed that both iCAR and the cellular system under consideration use the same amount of spectral bandwidth (resources) though in different ways. This is in contrast to the assumption in the previous studies where the unlicensed Industrial, Science and Medical (ISM) band channel, used for relaying, was assumed free of cost. Our results show that with the same amount of channel resource as in conventional cellular systems and a limited number of ARS's, the iCAR system can reduce hand-off call dropping probability significantly and achieve higher channel efficiency. We expect that the analytical and simulation models developed for iCAR will also provide new directions of research for other integrated heterogeneous networks, such as the coverage overlaid wireless systems (ranging from satellite to Bluetooth).

The rest of this paper is organized as follows. Section 2 reviews the basic operations of the iCAR system. Section 3 discusses an analytical model for hand-off calls in iCAR. Section 4 provides the simulation results and discussions. Finally, Section 5 concludes the paper.

2. An overview of iCAR system

In this section, we briefly describe basic operations and main benefits of iCAR (see [29] for more details). To simplify the following presentation, we focus on cellular systems where all BTS's are controlled by a Mobile Switching Center (MSC) [21].

The basic idea of the iCAR system is to place a number of ARS's throughout the geographical coverage area to relay the signals between the MH's in the congested cell and BTS's in the non-congested cell. Each ARS and MH in the iCAR system has two air-interfaces, the **C** (for cellular) interface for communications with a BTS and the **R** (for relaying) interface for communicating with an MH or an ARS. The R interface uses a separate set of channels so that it has no interference to the transmission at the C-interface. Note that, although the R-interface, which is similar to that used in wireless LANs or ad hoc networks (see for example [3,5,17]), can operate at the unlicensed ISM band (i.e., utilize the "free" spectrum), one can also reserve a number of DCH's in the licensed cellular band for relaying, so that the iCAR system does not consume more bandwidth than a conventional cellular system does. Moreover, the special medium access control (MAC) protocol, such as signature laced communication, or use of smart antenna, can be adopted for relaying so that the interference between the R-interfaces and the delay over multi-hop relay are minimized. In addition, because multiple ARS's can be used for relaying, the transmission range of each ARS using its R interface can be much shorter than that of a BTS, which implies that an ARS can be much smaller and less costly than a BTS. It is worth mentioning that, to install a new BTS in the crowded downtown area could be very expensive because of not only the equipment cost but also the right of way to install the equipment and the cost for system planning, which make

[1] Here we consider a FDMA system. In TDMA and CDMA systems, DCA and channel borrowing approaches are less efficient [22].

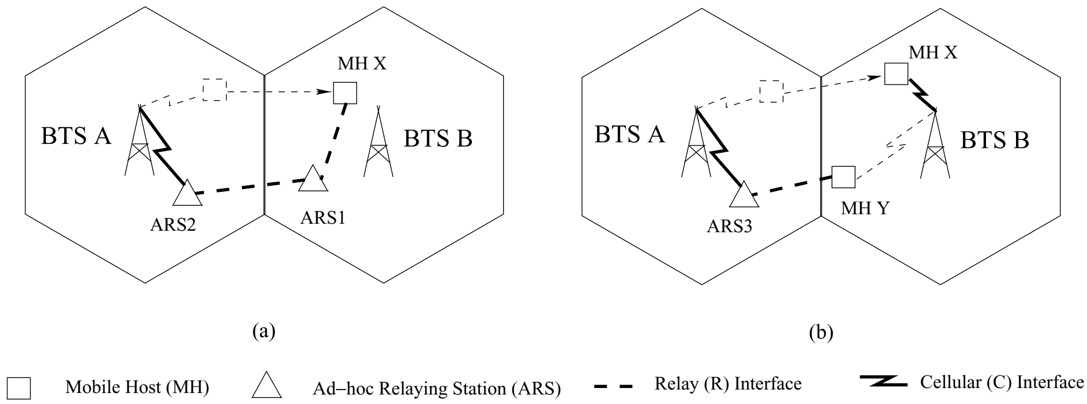

Figure 2. Two examples of relaying operations in iCAR. (a) A relaying example where MH X communicates with BTS A through two Mobile Relaying Stations (ARS's); (b) Secondary relaying to free up a channel for MH X.

the conventional approaches (such as cell splitting [10,14]) unattractive to increase the system capacity.

In present cellular systems, if an MH is involved in a hand-off (or new) call (as a caller or callee) in a congested cell and is unable to find a DCH, the hand-off (or new) call will be dropped (or blocked). For example, consider a scenario in figure 2 where MH X is currently involved in a call and is moving out of cell A into cell B which is congested (i.e., does not have any available DCH's at this time), a request for hand-off will be sent as soon as the power level from BTS A received by MH X goes below a certain threshold (and that from BTS B is becoming higher). A successful hand-off will take place, usually within a few hundred milliseconds (depending on the moving speed of the MH) before the received power from BTS A reaches an unacceptable level [11,21,25]. If the congestion in cell B persists for a period of time during which the MH moves farther away from BTS A thus causing the received power level from BTS A to fall below the acceptable level, hand-off will fail and the call will be dropped [7,20,30].

However in iCAR, the call does not have to be dropped even though the congestion in cell B persists. More specifically, when MH X moves into the congested cell B, it can communicate with an ARS in cell A, possibly through other ARS's in cell B (see figure 2(a) for an example). We call this strategy that establishes a relaying route between MH X (moving into a congested cell) and a BTS in a nearby non-congested cell *primary relaying*. With primary relaying, MH X can continue to communicate with BTS A through relaying. If primary relaying is not possible because, for example in figure 2(a), ARS 1 is not close enough to MH X to be a *proxy* (and there are no other nearby ARS's), one may resort to *secondary relaying*. A basic case is illustrated in figure 2(b), where MH Y denotes any active MH in cell B which is currently involved in a call. As shown in figure 2(b), MH Y is within the coverage area of ARS 3, therefore, one may establish a relaying route between MH Y and BTS A, so that MH Y can use the DCH in cell A via relaying. Accordingly, the channel released by MH Y in cell B can be assigned to MH X. Since cell B is a congested cell, it implies that there are many on-going calls in cell B, and there is a high probability that at least one active MH (like MH Y) can be found even when there are only a limited number of ARS's in the system.

Note that, although a hand-off call may be supported in the cellular system when the MH involved in the call *just* moves into cell B (i.e., the MH is still around the cell boundary) due to the overlapped cell coverage or the soft hand-off (and/or cell breathing) in the CDMA [26] system, the call will be eventually dropped while the MH moves farther away from BTS A. But in iCAR, due to the multi-hop relaying via ARS's, the relaying path can extend to any area inside a cell, and thus further reduce the dropping probability of the hand-off calls. In addition, the primary and secondary relaying operations can not only balance traffic load but also *effectively* and *dynamically* share the DCH's between the cells in iCAR. Two theorems and the analytical model as well as the results presented in [28,29] have shown that channel sharing can significantly improve the channel efficiency and reduce the request blocking probability, even when the traffic load is balanced among the cells.

3. Hand-off performance analysis in iCAR

In this section, we introduce an analytical model for the hand-off calls in iCAR. We first derive the probability that a given hand-off attempt fails, and then compute the probability that a hand-off attempt occurs. The readers are also referred to [15] for the hand-off analysis in a conventional cellular system.

For simplicity, we assume that there is unlimited relaying bandwidth (used by the R interface). Although this assumption is not very practical, as it grants more spectrum resource to the iCAR system resulting in an unfair comparison with the cellular system, the analytical model provides insight into the behavior of the hand-off call dropping probability in iCAR. In Section 4, we will conduct simulations with more realistic assumptions. We also assume that there is no priority given to the hand-off requests. In other words, there are no channels reserved for the hand-off calls, and a hand-off request will be blocked immediately without queuing when there is no channel available. In addition, we ignore buffer time for hand-off calls due to the overlapped cell coverage or soft hand-off

Table 1
List of Notations used in analysis.

M	Number of DCH's in a cell.
p_L	Line coverage of the ARS's.
p_A	Area coverage of the ARS's.
T_M	Unencumbered duration of a new call or a hand-off call.
T_R	Hand-off buffer time.
T_{AH}	Time an MH resides in the ARS coverage where the call (via relaying) is originated.
T_n	Time an MH resides in the cell where the call is originated.
T_h	Time an MH resides in the cell where the call is handed off.
P_{Bj}^o	Blocking probability of a cell j in a conventional cellular system.
P_{Bj}^r	Blocking probability of a cell j in an iCAR system.
P_B^o	Blocking probability of a cell in a conventional cellular system.
P_B^r	Blocking probability of a cell in an iCAR system.
P_{A-B}	Dropping probability of a given hand-off attempt from an ARS to a BTS.
P_{B-B}	Dropping probability of a given hand-off attempt from a BTS to a BTS.
P_N	Probability that a non-blocked new call requires at least one hand-off before completion.
P_H	Probability that a hand-off call requires another hand-off before completion.
P_R	Probability that a call is supported via relaying.
P_{AH}	Probability that an ARS-to-BTS hand-off attempt happens given the call is supported via relaying.
P_A	Probability that an ARS-to-BTS hand-off happens in a cell.
P_{FH}	Probability that a non-blocked new call is dropped.
P_d^r	Dropping probability of iCAR.

as this can be present in both the conventional cellular system and iCAR but instead, focus on the benefits of being able to perform hand-offs between BTS and ARS, which effectively increases the hand-off call buffer time. We consider a system where one ARS is placed at each shared border of two cells, and assume p_A to be the *area* coverage of the ARS's which is a fraction of the cell area covered by the ARS's, and p_L to be the *line* coverage of the ARS's which is a fraction of the cell border covered by the ARS's.

We define a random variable T_M with an exponential distribution[2] to denote the unencumbered duration of a new call or a hand-off call. The density function of T_M is

$$f_{\mathbf{T_M}}(t) = \begin{cases} \mu e^{-\mu t}, & t > 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where $\frac{1}{\mu}$ is the mean value of T_M. We assume that the speed (v) and the moving direction (θ) of an MH are uniformly distributed random variables but remains constant in a cell. The respective density functions are given by

$$f_{\mathbf{V}}(v) = \begin{cases} \dfrac{1}{V_{\max}}, & 0 \le v \le V_{\max} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $V_{\max}$ is the maximum velocity of an MH, and

$$f_{\Theta}(\theta) = \begin{cases} \dfrac{1}{\pi}, & 0 \le \theta \le \pi \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Note that, although the moving direction of the MH corresponding to a new call may be from 0 to 2π, we can consider the range of $[0, \pi]$ only, because of the symmetry. The moving direction for a hand-off call is assumed to be from 0 to π (i.e., the active MH does not move back to the cell where it was located).

We denote the blocking probability of a cell j in a conventional cellular system (i.e., without relaying) by P_{Bj}^o and that in an iCAR system (i.e., with relaying) by P_{Bj}^r. P_{Bj}^o and P_{Bj}^r can be obtained from the existing analytical models [12] and [28], respectively. M denotes the number of DCH's in each cell.

3.1. *Hand-off attempt failure probability*

We first discuss the probability that a given hand-off attempt fails. There are two types of hand-off in iCAR : BTS-to-BTS hand-off and ARS-to-BTS hand-off. In the former, a connection *without relaying* is handed over from one BTS to another, while in the latter, a connection *via relaying* is handed over from an ARS to a BTS.

3.1.1. *ARS-to-BTS hand-off*

Given the assumption of no priority for the hand-off attempts, the probability that a hand-off attempt from an ARS to a BTS j will be rejected is

$$P_{A-B} = P_{Bj}^r \tag{4}$$

3.1.2. *BTS-to-BTS hand-off*

For a hand-off attempt from BTS_i to BTS_j (see figure 3 for example), the probability that it fails in a conventional cellular system is equal to the blocking probability of cell j (without relaying), i.e., P_{Bj}^o.

In the iCAR system, when an MH crosses the shared border of two cells, it may be covered by ARS's with a probability p_L. If the MH associated with the hand-off attempt is not covered

[2] Although recent research [8] shows that the hand-off call duration obeys more of a lognormal distribution or shifted exponential distribution rather than a standard exponential distribution, for analytical tractability we will use an ideal exponential pdf in this paper. iCAR handoff performance with non-exponential call duration [9] will be studied in our future work.

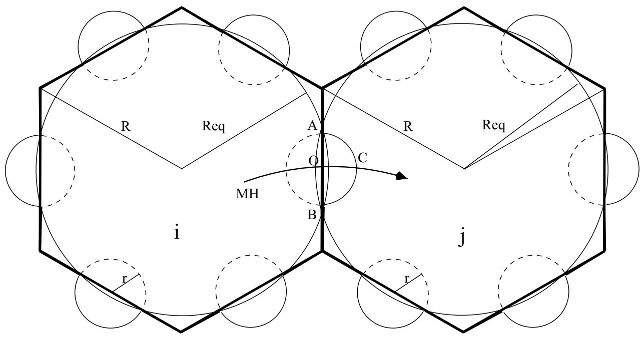

Figure 3. An example of call hand-off.

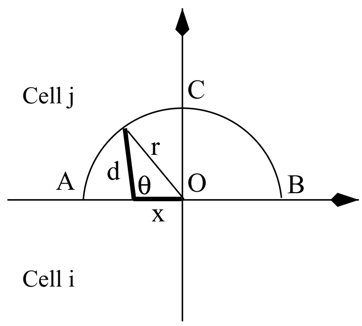

Figure 4. T_R analysis.

by an ARS, the probability of this attempt being rejected is equal to the blocking probability of cell j (with relaying), i.e., P^r_{Bj}. On the other hand, if the MH involved in the hand-off is covered by an ARS (i.e., crossing line AOB in figure 3), it will try a normal BTS-to-BTS hand-off and succeed if there are free DCH's available in cell j. Otherwise, it will still use the DCH of BTS_i via relaying through the ARS until one DCH of BTS_j is released so that the MH may use the released DCH, or the call is finished, or the MH moves out of the coverage of the ARS. We define a random variable T_R to be the time duration of an MH travelling within the coverage of the ARS after crossing the cell border (i.e., the time of the MH travelling from a point on the line AOB to a point on the curve ACB in figure 3). In other words, the MH has the additional time of up to T_R to complete the hand-off process, and we call this period the *hand-off buffer time* in iCAR. Because of the hand-off buffer time, the hand-off attempt will be rejected only when

1. all DCH's in cell j are busy (even with relaying) at the moment when the MH crosses the shared border of the two cells (with a probability of P^r_{Bj}), and
2. the remaining call duration is longer than the hand-off buffer time (with a probability of $P_r\{T_M > T_R\}$), and
3. there is no DCH in cell j to be released, i.e., none of the ongoing calls in cell j is finished and no active MH moves out from cell j within the hand-off buffer time (with a probability of $[P_r\{T_M > T_R\} \cdot (1 - P_N)]^M$, where P_N is the probability that a non-blocked new call requires at least one hand-off before completion, which will be discussed later in Section 3.2).

Based on the above conditions, the probability that a BTS-to-BTS hand-off attempt will be rejected in iCAR is

$$\begin{aligned} P_{B-B} = (1 - p_L) \cdot P^r_{Bj} + p_L \cdot P^r_{Bj} \cdot P_r\{T_M > T_R\} \\ \cdot [P_r\{T_M > T_R\} \cdot (1 - P_N)]^M \end{aligned} \tag{5}$$

where the probability of $T_M > T_R$ is given by

$$P_r\{T_M > T_R\} = \int_0^\infty \left[1 - F_{T_M}(t)\right] f_{T_R}(t)\, dt \tag{6}$$

In equation (5), M and p_L are the known iCAR system design parameters. The call duration T_M, being exponentially distributed with a mean value of $\frac{1}{\mu}$, is also known. P^r_{Bj} is obtained from the analytical model developed by Wu et al. [28]. The distribution of T_R is yet to be determined.

In order to obtain the density function of T_R, we consider the ARS at the shared border of cell i and cell j (see figure 4), and first derive the density function of the random variable d, which is the distance that an MH travels before it moves out of the coverage of an ARS (i.e., the distance from a point on line AOB to a point on the curve ACB as shown in figure 4).

Let us denote r to be the transmission range of an ARS and X be the random variable representing the distance from an MH on the line AOB to the origin O. Assuming that an MH has equal probability to appear at any position on line AOB,

$$f_{\mathbf{x}}(x) = \begin{cases} \dfrac{1}{r}, & 0 \le x \le r \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

From figure 4, we have

$$r^2 = d^2 + x^2 - 2dx\cos\theta \tag{8}$$

Since d is a function of two random variables x and θ, we can derive the density function of d (i.e., $f_{\mathbf{D}}(d)$) by defining an auxiliary variable $w = x$, so that $\theta = arccos(\frac{d^2+w^2-r^2}{2dw})$ and $x = w$. Accordingly, the Jacobian transformation is

$$\begin{aligned} J^{-1} &= \begin{vmatrix} \frac{\partial\theta}{\partial d} & \frac{\partial\theta}{\partial w} \\ \frac{\partial x}{\partial d} & \frac{\partial x}{\partial w} \end{vmatrix} = \left|\frac{\partial\theta}{\partial d}\right| \\ &= \left|\frac{w^2 - d^2 - r^2}{d\sqrt{4d^2w^2 - (d^2 + w^2 - r^2)^2}}\right| \\ &= \frac{d^2 + r^2 - w^2}{d\sqrt{4d^2w^2 - (d^2 + w^2 - r^2)^2}} \end{aligned} \tag{9}$$

and yields the joint density function of d and w

$$\begin{aligned} f_{\mathbf{DW}}(d, w) &= J^{-1} f_{\mathbf{x}\Theta}\left(w, \arccos\left(\frac{d^2 + w^2 - r^2}{2dw}\right)\right) \\ &= J^{-1} \cdot \frac{1}{r} \cdot \frac{1}{\pi} \qquad (|d - r| \le w \le r) \end{aligned} \tag{10}$$

Hence, the density function of d is given by

$$f_{\mathbf{D}}(d) = \int_{|d-r|}^{r} f_{dw}(d, w)\, dw \tag{11}$$

The hand-off buffer time is given by

$$T_R = \frac{D}{V} \tag{12}$$

with the corresponding density function

$$\begin{aligned} f_{\mathbf{T_R}}(t) &= \int_0^{V\max} |v| f_{DV}(tv, v)\, dv \\ &= \int_0^{V\max} v f_D(tv) f_V(v)\, dv \end{aligned} \tag{13}$$

where $f_D(\cdot)$ and $f_V(\cdot)$ are obtained from equations (11) and (2), respectively.

Finally, we substitute the expression for f_{T_R} into equation (6) to obtain $P_r\{T_M > T_R\}$, and compute P_{B-B} using equation (5). As it is difficult to obtain a closed-form expression for f_{T_R}, we compute $P_r\{T_M > T_R\}$ and P_{B-B} numerically, and the results are presented in Section 3.4.

3.2. Probability that a hand-off attempt occurs

In this subsection, we derive the probability that a hand-off attempt occurs.

3.2.1. BTS-to-BTS hand-off

The probability that a BTS-to-BTS hand-off attempt occurs may be obtained in a similar way as that introduced in [15] for a conventional cellular system. More specifically, denoting T_n to be the random variable representing the time for which an MH resides in the cell where the call is originated, and T_h to be the random variable representing the time for which an MH resides in the cell where the call is handed off, we may obtain the probability that a non-blocked new call requires at least one hand-off before completion (P_N), and the probability that a hand-off call requires another hand-off before completion (P_H) as follows.

$$P_N = P_r\{T_M > T_n\} = \int_0^\infty \left[1 - F_{T_M}(t)\right] f_{T_n}(t)\, dt \tag{14}$$

$$P_H = P_r\{T_M > T_h\} = \int_0^\infty \left[1 - F_{T_M}(t)\right] f_{T_h}(t)\, dt \tag{15}$$

Approximating the cell (which is modelled as a hexagon) to be a circle with the same coverage (see the circle with radius R_{eq} in figure 3), we may obtain the estimation of the distribution function of T_n and T_h in a similar way as that we used to obtain T_R. The only difference is that, in the case to obtain T_R, the MH can only appear *on* a *line* (i.e., line AOB in figure 3), however for the case to obtain T_n and T_h, the MH may appear at any position *within* and *on* the *circle* with radius R_{eq}, respectively. Thus, the details on derivation of T_n and T_h are omitted.

3.2.2. ARS-to-BTS hand-off

The probability that an ARS-to-BTS hand-off happens in a cell (P_A) is

$$P_A = P_{AH} \times P_R \tag{16}$$

where P_{AH} is the probability that an ARS-to-BTS hand-off attempt may happen given the call is supported via relaying, and P_R is the probability that a call is supported via relaying. Similar to P_N,

$$\begin{aligned} P_{AH} &= P_r\{T_M > T_{AH}\} \\ &= \int_0^\infty \left[1 - F_{T_M}(t)\right] f_{T_{AH}}(t) dt \end{aligned} \tag{17}$$

in which T_{AH} is a random variable of the time duration of an MH travelling within the coverage of the ARS, assuming it starts a call via relaying at any position within the ARS coverage. Its distribution function may be obtained in a similar way to that used to derive T_n.

In each cell, there is a one-to-one mapping between the calls supported via relaying and the calls that would be blocked in a conventional system but are accepted because of using primary or secondary relaying. Thus, we may estimate P_R as $P_B^o - P_B^r$, where P_B^o and P_B^r are the average blocking probabilities without and with relaying in a cell, and then, compute the probability that an ARS-to-BTS hand-off happens (P_A).

3.3. Call dropping probability in iCAR

In this subsection, we derive the call dropping probability of an iCAR system based on the above discussions. We assume that all cells in an iCAR system have the same average traffic intensity and the same average call blocking probability (P_B^r). Thus, the probability that a non-blocked new call is dropped in the L-th cell, i.e. it

1. succeeds in the first $L - 1$ BTS-to-BTS hand-off attempts (with a probability of $P_N P_H^{(L-2)}(1 - P_{B-B})^{(L-1)}$),
2. and succeeds in the ARS-to-BTS hand-offs in the first $L-1$ cells (with a probability of $P_A^{(L-1)}(1 - P_{A-B})^{(L-1)}$),
3. but fails on the L-th BTS-to-BTS hand-off attempt (with a probability of P_{B-B}),
4. or even though it succeeds on the L-th BTS-to-BTS hand-off attempt, it fails on the ARS-to-BTS hand-offs in the L-th cell (with a probability of $(1 - P_{B-B}) P_A P_{A-B}$),

is

$$\begin{aligned} P_{FH}^L &= [P_{B-B} + (1 - P_{B-B}) P_A P_{A-B}] \\ &\quad \cdot \left[P_N P_H^{(L-1)} (1 - P_{B-B})^{(L-1)} P_A^{(L-1)} (1 - P_{A-B})^{(L-1)}\right] \end{aligned}$$

Accordingly, the probability that a non-blocked new call will be dropped is,

$$P_{FH} = \sum_{L=1}^{\infty} P_{FH}^L \tag{19}$$

and the dropping probability of an iCAR system P_d^r is

$$P_d^r = \left(1 - P_B^r\right) \cdot P_{FH} \tag{20}$$

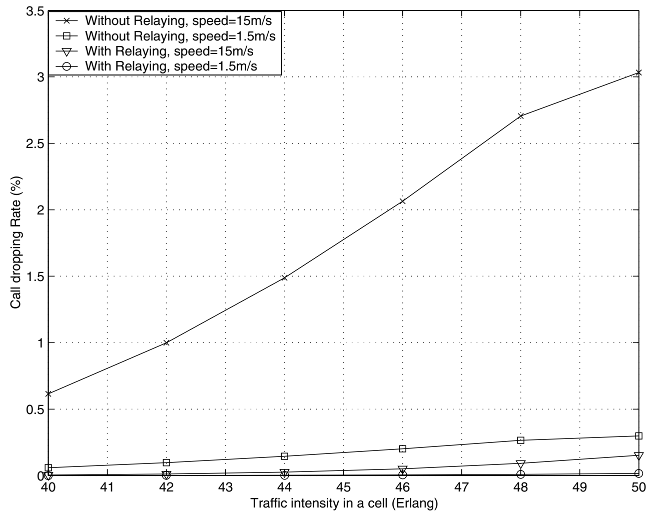

Figure 5. Call Dropping rates for different MH moving speeds. $\mu = 1/120$.

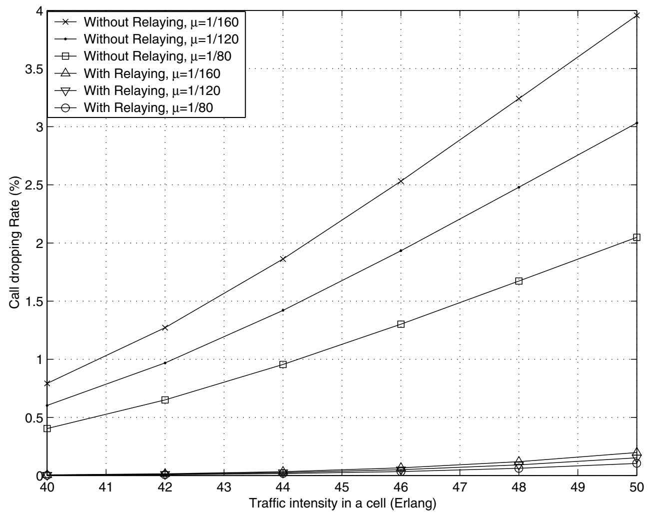

Figure 6. Call Dropping rates for different μ values. MH moving speed is 15 m/s.

3.4. Results

We now present the numeric results for the hand-off call dropping probability in an iCAR system. Average traffic intensity in a cell is considered to be varying from 40 to 50 *Erlangs*, and each cell has the same number of data channels ($M = 50$). We assume the center-to-vertex distance of a cell is $R = 2000$ meters, and thus $R_{eq} = \sqrt{\frac{6\sqrt{3}}{4\pi}} \times R = 1820$ meters. The ARS transmission range r is assumed to be 500 meters, which corresponds to $p_L = 0.5$ and $p_A = 0.23$ when users are uniformly distributed.

We first compute the call dropping probability of the systems with and without relaying under different MH mobilities, where the average call duration is assumed to be fixed at 120 sec. As shown in figure 5, the iCAR system has a much lower call dropping probability than that of a conventional cellular system. The performance gain in the iCAR system is due to the added hand-off buffer time contributed by the relays. As expected, the call dropping probability increases with the MH moving speed, because the higher MH mobility results in higher probability that an active MH may move out of the coverage of a BTS or an ARS, and consequently the higher probability that a hand-off attempt occurs (i.e., P_H, P_N, and P_A). As an example, when the MH moving speed increases from 1.5 m/s to 15 m/s, the call dropping probability increases by about 10 times in both the conventional cellular system and iCAR. Figure 5 also shows that the call dropping probability increases with the traffic intensity. This is because higher traffic intensity results in lesser channel resource availability at any cell, which affects new calls as well as hand-off calls.

Unlike call blocking probability, call dropping probability may vary widely under different average call duration values (i.e., $1/\mu$), even though the traffic intensity is the same. As shown in figure 6, a higher call duration results in a higher call dropping probability, because increasing the call duration increases the probability of hand-off attempt, and ultimately the call dropping rate.

4. Simulation and discussions

To evaluate hand-off performance (i.e., call dropping probability) under more realistic assumptions, we have developed a simulation model using the PARSEC language [2] and the GloMoSim simulator [31]. In this simulation, we consider a system with one ARS placed at each shared border of two cells, while all cells have the same average traffic intensity and the same number of DCH's (50). Also, the MH mobility is assumed to be uniformly distributed.

In our previous studies [28,29], we have compared the call blocking probability of iCAR with that of a cellular system having the same number of DCHs, but the former uses additional unlicensed band for relaying. In this paper we consider a cellular structure with channel reuse factor 7. In order to make a fair comparison, we assume that in a 7-cell cluster there are 7 additional channels available either for use as additional DCH's in conventional cellular system or for relaying as in iCAR. This assumption ensures that the iCAR system does not consume more bandwidth than that used by a conventional cellular system. To satisfy the co-channel interference constraint in conventional cellular system, each cell in a 7-cell reuse cluster gets one out of 7 additional channels. As a result, each BTS (i.e., cell) in the conventional cellular system, used for comparing with iCAR, has 51 DCH's. On the other hand, due to possible interference at the R-interface, the number of calls that an ARS can relay simultaneously can also be less than 7. In our simulation model, we assume that an ARS can relay a maximum of 5 calls simultaneously. Note that the co-channel interference at the R-interface is less critical, as the number of ARS's are limited compared to the number of MH's. By adopting special MAC protocol, such as

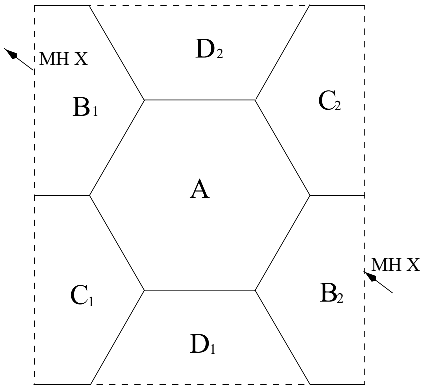

Figure 7. Simulation environment.

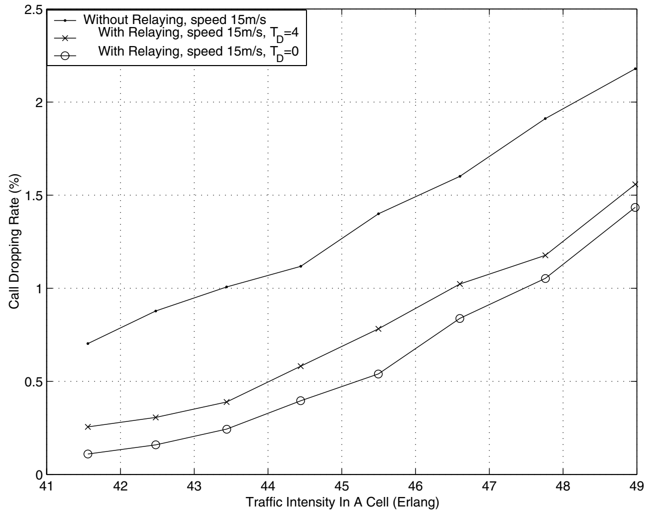

Figure 8. Call dropping rates with various M_D. Maximum MH moving speed is 15 m/s; call duration is 120 s.

signature-laced ARS-to-ARS communication, or use of smart antennas [19], the relaying channel interference can be effectively minimized.

The analytical model assumes a large system with unlimited number of independent cells, and thus an MH will never reach the boundary of the system. However, it is very difficult, if not impossible, to simulate such a large system. Instead, we use a novel design as shown in figure 7, which includes a cell A and six *half-cells*. Two corresponding half-cells (e.g., B_1 and B_2, or C_1 and C_2, or D_1 and D_2) form one cell, sharing the same BTS. When an MH X moves out of a half-cell (e.g., B_1) through the dashed line, it will enter the corresponding half-cell (e.g., B_2) without a hand-off. We consider the calls originated in cell A, and observe the dropping rate. Note that, an active MH may pass through a cell several times before the call terminates, therefore the cells cannot be assumed independent as we did in analysis.

In the analysis, we have assumed that a call via relaying will be switched from the proxy ARS to the BTS as soon as there is a DCH available at the BTS. Although this strategy results in the lowest call dropping probability, it may not be efficient for a real system. Specifically, when the traffic intensity is high, an active MH may switch over frequently between an ARS and a BTS because the secondary relaying requests may need the on-going call to be switched back to the ARS soon after it was switched to the BTS, and consequently results in a large amount of signaling overhead. In this simulation, we assume that the call will not be switched over to the BTS if the number of DCH's at the BTS is lower than a certain threshold (M_D), unless it would be dropped otherwise.

Figure 8 shows the call dropping rates for a conventional cellular system and an iCAR system with different values of M_D, where the call duration and the MH moving speed are fixed to be 120 sec and 15 m/s, respectively. As we can see, the iCAR system has a significantly lower call dropping rates than that of a conventional cellular system. Moreover, the iCAR system using a lower M_D has a lower call dropping rate, which, however, has the tradeoff for a larger amount of signaling overhead. For instance, the number of signaling messages when $M_D = 0$ is about 50% more than that when $M_D = 4$.

We also notice that the call dropping rates obtained from the simulations are higher than the analytical results. There are several reasons. Firstly, the cells in the simulation are correlated, but they are assumed to be independent in the analysis. Secondly, the cells are approximated as circles in the analytical model, which may affect T_n and T_h, and consequently P_N and P_H. Thirdly, the number of relaying channels in the analytical model is unlimited, while the simulation assumes 7 relaying channels (in which 5 can be used simultaneously) for each ARS. Fourthly, we have ignored the signaling overhead in analysis. Finally, the value of B_B^r obtained from the analytical model is lower than that in the simulation (see [28] for more discussion).

Figure 9 shows the call dropping rate under various MH moving speeds and the average call duration. Both of these two factors have significant effect on the probability of

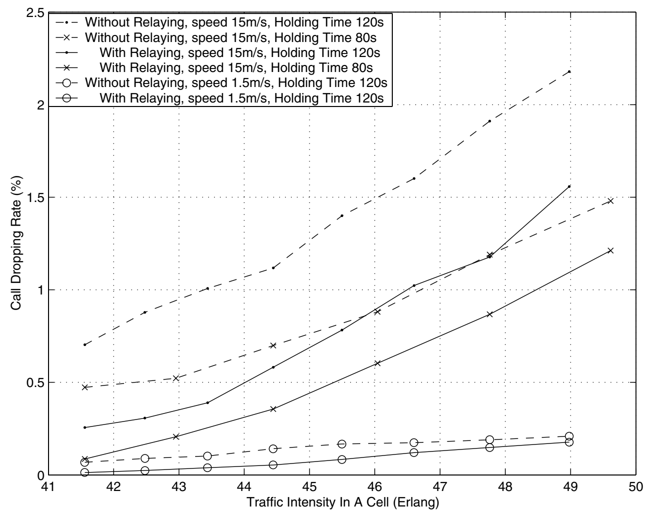

Figure 9. Call dropping rates with various MH moving speeds and call duration. $M_D = 4$.

hand-off attempt (i.e., P_N, P_H, and P_A), and accordingly the call dropping rates. The results verify the capability of iCAR to improve the hand-off performance under various conditions. Within the normal operation range (e.g., when the traffic intensity in a hot cell is lower than 45 $Erlangs$), the iCAR system can reduce the call dropping probability by up to 50% of that of a cellular system. Also, along the line of analytical observations, higher moving speed and longer call duration result in higher call dropping rates in both the conventional cellular system and the iCAR system.

In the above study, we have assumed that a request will be blocked immediately if there are no DCH's available (i.e., a so called *loss system*). We also simulate a *queuing system*, where an immediately unsuccessful hand-off request may be queued for a finite time(t) for further attempts, before it is rejected. We implement a First In First Out (FIFO) queue at each BTS. The hand-off requests (as well as the new call requests) are rejected only when there are no free DCH's and their queuing time exceed t. Figure 10 shows the call dropping rates in the systems with various maximum queuing time. One may observe that the iCAR system helps reduce the call dropping probability in the queuing system as well. In addition, the systems that allow a longer queuing time have a lower call dropping probability.

It may be noted that all results obtained in this work are under the assumption that there is no priority for hand-off calls, i.e., there are no channels reserved for hand-off requests. However, a conventional cellular system usually reserves a certain number of channels to accommodate the hand-off attempts in order to reduce the call dropping probability of hand-off calls. But this also increases the blocking probability for new calls. The relays in an iCAR system introduce the added buffer time for hand-off calls. Thus, unlike the conventional cellular systems, the iCAR may not require reserving any channels for hand-off calls, yet it performs better and at the same time increases channel efficiency.

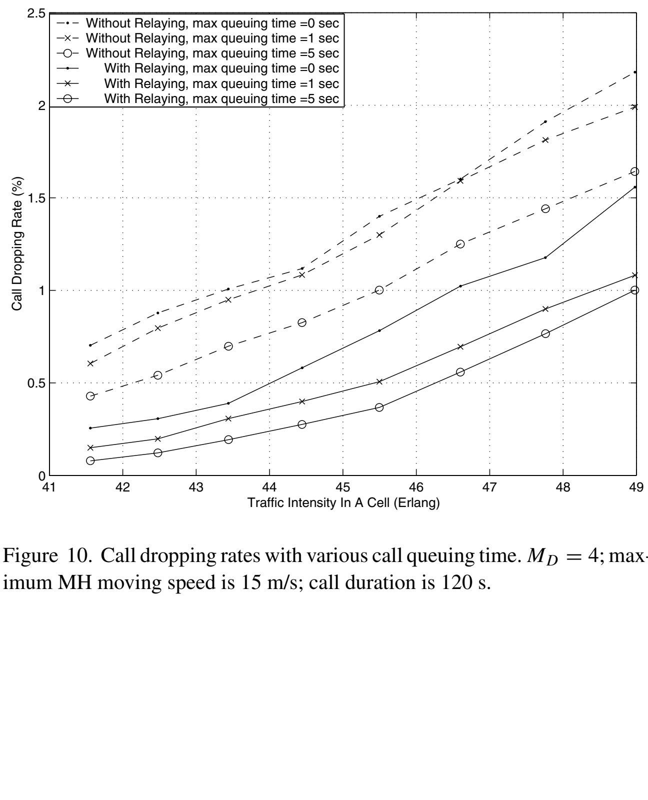

Figure 10. Call dropping rates with various call queuing time. $M_D = 4$; maximum MH moving speed is 15 m/s; call duration is 120 s.

5. Conclusion

In this paper, we have studied hand-offs in iCAR, which can occur among the BTS's as well as between BTS's and ARS's. The latter is an example of inter-system hand-off involving heterogenous wireless technologies. We have evaluated the hand-off performance in terms of call dropping probability via analysis and simulation. Through a more realistic simulation model, the analytically observed trends have been verified. We have shown that an iCAR system, with a limited number of relaying channels and under comparable (or equal) bandwidth assumptions, has significantly reduced hand-off call dropping probability and achieved higher channel efficiency over the conventional cellular system. Our simulation results indicate that under normal traffic load the call dropping probability of the iCAR system can be reduced by up to 50% of that in the conventional cellular system. In our future work, we will study iCAR handoff performance with more realistic mobility models and non-exponential channel holding time as discussed in [9].

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