Queuing Delay Performance of the Integrated Cellular and Ad hoc Relaying System

Hongyi Wu, Swades De, Chunming Qiao, Evsen Yanmaz, and Ozan Tonguz

***Abstract*— The *Integrated Cellular and Ad hoc Relaying (iCAR)* system is a representative heterogeneous wireless system, proposed to address the congestion problem in the wireless networks. In this paper, we present an analytic model based on Markov chains for the queuing delay performance of iCAR. Our results show that the new call requests in iCAR have a significantly lower queuing delay than that of the conventional cellular system. The analytic model developed in this paper may serve as the guideline for the delay performance evaluation of the next generation heterogeneous wireless systems.**

***Index Terms*—Queuing Delay, iCAR, Cellular, Ad hoc, Relay**

I. Introduction

Various efforts for providing wireless access services, such as Cellular Systems [1], Wireless Local Area Networks (WLANs) [2], Mobile Ad hoc Networks (MANET) [3], [4], [5], Bluetooth [6], and Sensor Networks [7], are stimulating the growth of wireless traffic and the requirement for a ubiquitous wireless infrastructure. The *Integrated Cellular and Ad hoc Relaying (iCAR)* system [8] has been proposed to deploy the ad hoc networking technology in the cellular system to address the congestion problems due to limited wireless bandwidth and dynamically varying traffic load. By using the *Ad hoc Relaying Stations (ARSs)* along with the signaling and routing protocols presented in [9], it is possible to divert traffic from one (possibly congested) cell to another (non-congested) cell. iCAR, with its ability to leverage both the cellular and ad hoc relaying techniques to increase system's capacity, is a promising evolution path to the next generation heterogeneous system.

In [8], [10], the performance of iCAR in terms of the call blocking probability has been studied via analysis and simulations. It has been shown that iCAR can 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 can achieve. Recent studies on hand-off performance in iCAR [11] has shown that with the same amount of 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.

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The analysis in [8], [10], [11] assumed a *loss* system, where a call experiencing congestion is discarded immediately. In this paper, we consider the iCAR system with *queueing* capability, where a call can wait in the incoming buffer at the congested Base Transceiver Station (BTS) if no channel is immediately available. We develop an analytic model based on Markov chains, and compare the queueing delay performance of iCAR with that of conventional cellular systems. The rest of this paper is organized as follows. Sec. II introduces the background of the iCAR system. Sec. III presents the analytic model. Sec. IV shows the results. Finally, Sec. V concludes the paper.

II. Background

The basic idea of iCAR is to deploy a number of *Ad hoc Relaying Stations (ARSs)* to relay the calls of the mobile hosts (MHs) in the congested cell to the BTSs in nearby non-congested cells. An example of relaying is illustrated in Fig. 1 where MH X in cell A (which is congested, i.e., in which there are a number of calls waiting in the queue) communicates with the BTS in cell B (or BTS B, which is non-congested) through two ARS's. Note that the ARS (as well as the MHs) need to have two air interfaces, the **C** (for cellular) interface for communicating with a BTS and the **R** (for relaying) interface for communicating with an MH or an ARS. The R-interface can be similar to that used in other ad hoc networks to form a wireless mesh routing network that overlays on top of existing cellular systems. It uses a separate set of channels to avoid the interference to the C-interface. Special medium access control (MAC) protocol, such as orthogonal codes, or smart antenna technics [12], can be adopted for relaying so that the R-channel interference and the delay over multihop relay are minimized.

There are two basic relaying operations in iCAR, namely, *primary relaying* and *secondary relaying*. In primary relaying, an MH X within a congested cell A may access a Data Channel (DCH) of a neighboring cell B via an ARS. A primary relaying attempt may fail because MH X is not covered by any ARSs or the relaying path cannot extend to a BTS with free channels. In such a case, the secondary relaying will be attempted, with which one may establish a relaying route between an active MH using a DCH in cell A (say MH Y) and BTS B, so that MH Y can free up its DCH in cell B for use by MH X. Similarly, the secondary relaying attempt may fail if none of the active MHs is covered by ARSs or no relaying path can extend to a BTS with free channels. The readers are also referred to [8] for a detailed description of the relaying operations in iCAR.

As established in [8], in the iCAR system, one cell can share its channels with other cells (via relaying) without violating

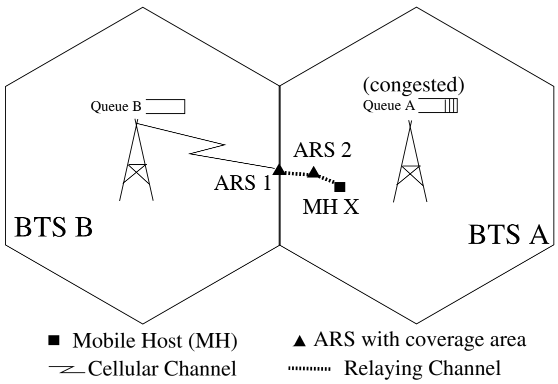

Fig. 1. A relaying example. The relaying route is established from MH X in a congested cell A to a BTS in the non-congested B through two ARSs.

the co-channel interference constraint which limits the effectiveness of the Dynamic Channel Allocation [13] or Channel Borrowing [14] approaches. Note that, due to channel sharing, iCAR can not only balance the traffic load between cells, but also improve the system performance (e.g., in terms of the reduced call blocking probability) even when the traffic load is evenly distributed in the network. In addition, although installing new BTSs (i.e., cell splitting [15]) or allocating more channels in each cell helps increase the system capacity, such an approach cannot increase per-channel utilization or efficiency. Finally, ARSs can be as small as the MHs. Thus they can be deployed much rapidly and economically than BTSs or more channels, and can be extended to anywhere in the system.

III. New Call Delay Analysis via Multidimensional Markov Chains

We consider an iCAR system with queuing capability, and analyze the waiting time and the waiting probability of a new call request. We assume that each BTS has M channels, and maintains a First In First Out (FIFO) queue with infinite buffer size. New calls arriving when all M channels are occupied and both primary and secondary relaying attempts are failed wait in the order of their arrival for free channels. However, a request via relaying will not be queued, i.e., it will be rejected immediately if there is no free DCH. For analytical tractability, we assume 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 queuing delay in iCAR. In Sec. IV, we will present a fair comparison between iCAR and the conventional cellular system, assuming both systems have the same amount of spectrum resource. We assume one ARS is placed at each shared border of two cells. The ARS coverage in terms of the percentage of a cell covered by ARSs is denoted by $0 < p \leq 1$. For simplicity, we assume that when considering a cell (say cell X), the traffic intensities of the six neighboring cells are equal and don't change as a result of relaying*. According to Erlang C formula [16], the probability that all channels are busy (b) in a neighboring cell of cell X (e.g., cell Y) at an arbitrary instant is,

$$b = \frac{\frac{T_Y^M}{M!} \cdot \frac{M}{M-T_Y}}{1 + T_Y + \frac{T_Y^2}{2!} + ... + \frac{T_Y^{M-1}}{(M-1)!} + \frac{T_Y^M}{M!} \cdot \frac{M}{M-T_Y}} \quad (1)$$

where T_Y is the traffic intensity of the cell Y.

In this section, we establish Markov chains to model both primary and secondary relaying, and derive the queuing delay of iCAR.

A. Primary Relaying

The state diagram for primary relaying is shown in Fig. 2, where state j means that there are j calls being served or waiting in the queue, λ_j and μ_j are the birth rate and death rate at state j, respectively. When $0 \leq j < M$, a state j may change to $j+1$ if a call arrives in cell X. Similarly, when a call completes in cell X ($j > 0$), the state j will change to $j-1$. When the current state is $j \geq M$, a new call request will be relayed to the neighboring cell if the corresponding MH is covered by ARSs and the neighboring cell has free DCHs (with a probability of $p(1-b)$). Otherwise, the request will be put into the queue, i.e., state j will change to state $j+1$ (with a probability of $(1-p+pb)$).

Denote by $Q(j)$ the steady state probability that the system is at state j. According to the state diagram, we can write the following state equations.

$j = 0$:

$$\lambda_0 \cdot Q(0) - \mu_1 \cdot Q(1) = 0 \quad (2)$$

$0 < j < M$:

$$(\mu_j + \lambda_j) \cdot Q(j) - \lambda_{j-1} \cdot Q(j-1) - \mu_{j+1} \cdot Q(j+1) = 0 \quad (3)$$

$j = M$:

$$[\mu_M + (1-p+pb)] \cdot Q(M) - \lambda_{M-1} \cdot Q(M-1) - \mu_{M+1} Q(M+1) = 0 \quad (4)$$

$j > M$:

$$[\mu_j + (1-p+pb)] \cdot Q(j) - (1-p+pb)\lambda_{j-1} \cdot Q(j-1) - \mu_{j+1} Q(j+1) = 0 \quad (5)$$

In addition,

$$\sum_{j=0}^{\infty} Q(j) = 1 \quad (6)$$

Here, we use a few classic assumptions, which are also used to derive the Erlang C formula. More specifically, we assume the probability of a new call arriving is independent of the number of busy sources, i.e. $\lambda_j = \lambda$ for some λ; and also, the death rate is proportional to the number of busy sources, i.e. $\mu_j = j\mu$ if $j < M$, and $\mu_j = M\mu$ if $j \geq M$, for some μ. Solving the above state equations, we can obtain the probability of each state ($Q(j)$, $j \geq 0$), and accordingly compute the call waiting time and waiting probability.

*We have shown in [10] that the arrival traffic via relaying is normally much less than the traffic originated in a cell, and thus has limited affect on the performance of this cell.

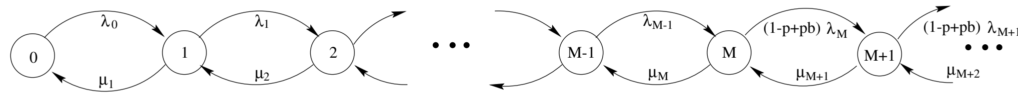

Fig. 2. State diagram for primary relaying in a cell X.

The probability that exactly k calls end during the time t is given by the Poisson distribution with the parameter μM [16]. Thus, given the current state to be $j \geq M$, the probability that the waiting time of a new call is longer than time t, or in other words, the probability of $j - M$ or less calls terminating during the time t, is

$$P_j(t) = \sum_{k=0}^{j-M} \frac{(\mu M t)^k}{k!} e^{-\mu M t},\ j \geq M \tag{7}$$

The summation through all j yields the probability of delay exceeding t for an incoming call in the iCAR system with primary relaying:

$$W_p(t) = \sum_{j=M}^{\infty} Q(j) P_j(t) \tag{8}$$

Accordingly, when primary relaying is used, the average waiting time of an incoming call is given by

$$\overline{W}_p = \int_0^{\infty} t W_p(t) dt \tag{9}$$

B. Secondary Relaying

Fig. 3 shows the state diagram for the secondary relaying. A state (i, j) $(i \leq j)$ in Fig. 3 means that there are j calls being served or waiting in the queue and i of the calls being served can release its DCH via relaying (i.e. the corresponding MHs are covered by ARS). Let $\lambda_{i,j}$ be the call arrival rate at state (i, j), then, $p\lambda_{i,j}$ is the arrival rate of calls covered by ARSs, while $(1-p)\lambda_{i,j}$ is the arrival rate of calls not covered by ARSs, if MHs are evenly distributed in a cell. $\mu_{i,j}$ is the death rate of active MHs covered by ARS at state (i, j), and $\bar{\mu}_{i,j}$ is the death rate of active MH not covered by ARS at state (i, j).

When $j < M$ and a new call comes in cell X at state (i, j), it will change to $(i+1, j+1)$ if the corresponding MH is covered by ARS, or change to $(i, j+1)$ if it is not covered by ARS. When $M \geq j > 0$ and a call finishes in cell X at state (i, j), it will change to $(i-1, j-1)$ if the corresponding MH is covered by ARS and was directly using a DCHs to access the system, or change to $(i, j-1)$ otherwise.

When $j \geq M$ and a new call comes in cell X at state (i, j), it may change to $(i-1, j)$ if primary relaying fails but secondary relaying successes (with a probability of $(1 - b^i)(1 - p + pb)$). Otherwise, if both primary and secondary relaying fail, the state (i, j) will change to state $(i, j+1)$ with a probability of $b^i(1 - p + pb)$. When a call ends, the state (i, j) may change to three possible states: (1) if the MH corresponding to the call ended (denoted by MH_d) is covered by ARSs and the MH corresponding to the first call request in the queue (denoted by MH_f) is not covered by ARSs, the state (i, j) will change to state $(i-1, j-1)$; (2) if both MH_d and MH_f are not covered by ARSs, or both MH_d and MH_f are covered by ARSs, the state (i, j) will change to state $(i, j-1)$; (3) if MH_d is not covered by ARSs but MH_f is covered by ARSs, the state (i, j) will change to state $(i+1, j-1)$.

Let $Q(i, j)$ be the probability that the system is at state (i, j), we can write the following state equations according to the state diagram.

$i = j = 0$:

$$\lambda_{0,0} \cdot Q(0,0) - \bar{\mu}_{0,1} \cdot Q(0,1) - \mu_{1,1} \cdot Q(1,1) = 0 \tag{10}$$

$i = 0,\ 0 < j < M$:

$$(\bar{\mu}_{0,j} + \lambda_{0,j}) \cdot Q(0,j) - (1-p) \cdot \lambda_{0,j-1} \cdot Q(0,j-1) - \mu_{1,j+1} \cdot Q(1,j+1) - \bar{\mu}_{0,j+1} \cdot Q(0,j+1) = 0 \tag{11}$$

$i = 0,\ j = M$:

$$[\bar{\mu}_{0,M} + (1-p+pb)] \cdot Q(0,M) - (1-p) \cdot \lambda_{0,M-1} \cdot Q(0,M-1) - (1-b) \cdot \lambda_{1,M} \cdot [(1-p) + p \times b] \cdot Q(1,M) - (1-p)\mu_{1,M+1} Q(1,M+1) - (1-p)\bar{\mu}_{0,M+1} Q(0,M+1) = 0 \tag{12}$$

$i = 0,\ j > M$:

$$[\bar{\mu}_{0,j} + (1-p+pb)] \cdot Q(0,j) - (1-p+pb) \cdot \lambda_{0,j-1} \cdot Q(0,j-1) - (1-b) \cdot \lambda_{1,j} \cdot [(1-p) + p \times b] \cdot Q(1,j) - (1-p)\mu_{1,j+1} Q(1,j+1) - (1-p)\bar{\mu}_{0,j+1} Q(0,j+1) = 0 \tag{13}$$

$i = j = M$:

$$(\mu_{M,M} + \lambda_{M,M} \cdot [(1-p) + p \times b]) \cdot Q(M,M) - p \cdot \lambda_{M-1,M-1} \cdot Q(M-1,M-1) - p\mu_{M,M+1} \cdot Q(M,M+1) - p\bar{\mu}_{M-1,M+1} Q(M-1,M+1) = 0 \tag{14}$$

$i = M,\ j > M$:

$$(\mu_{M,j} + \lambda_{M,j} \cdot [(1-p) + p \times b]) \cdot Q(M,j) - p\mu_{M,j+1} Q(M,j+1) - p\bar{\mu}_{M-1,j+1} Q(M-1,j+1) - b^M (1-p+pb) \cdot \lambda_{M,j-1} \cdot Q(M,j-1) = 0 \tag{15}$$

$0 < i < M,\ j = M$:

$$(\mu_{i,M} + \bar{\mu}_{i,M} + \lambda_{i,M}[(1-p) + p \times b]) \cdot Q(i,M) - (1-p) \cdot \lambda_{i,M-1} \cdot Q(i,M-1) - p \cdot \lambda_{i-1,M-1} \cdot Q(i-1,M-1) - (1-b^{i+1}) \cdot \lambda_{i+1,M} \cdot [(1-p) + p \times b] \cdot Q(i+1,M) - [p\mu_{i,M+1} + (1-p)\bar{\mu}_{i,M+1}] \cdot Q(i,M+1) - p\bar{\mu}_{i-1,M+1} Q(i-1,M+1) - (1-p)\mu_{i,M+1} Q(i+1,M+1) = 0 \tag{16}$$

$0 < i < M,\ j > M$:

$$(\mu_{i,j} + \bar{\mu}_{i,j} + \lambda_{i,j}[(1-p) + p \times b]) \cdot Q(i,M) - (1-b^{i+1}) \cdot \lambda_{i+1,j} \cdot [(1-p) + p \times b] \cdot Q(i+1,j) - p\bar{\mu}_{i-1,j+1} Q(i-1,j+1) - (1-p)\mu_{i+1,j+1} \cdot Q(i+1,j+1) - b^i (1-p+pb) \lambda_{i,j-1} Q(i,j-1) - [p\mu_{i,j+1} + (1-p)\bar{\mu}_{i,j+1}] Q(i,j+1) = 0 \tag{17}$$

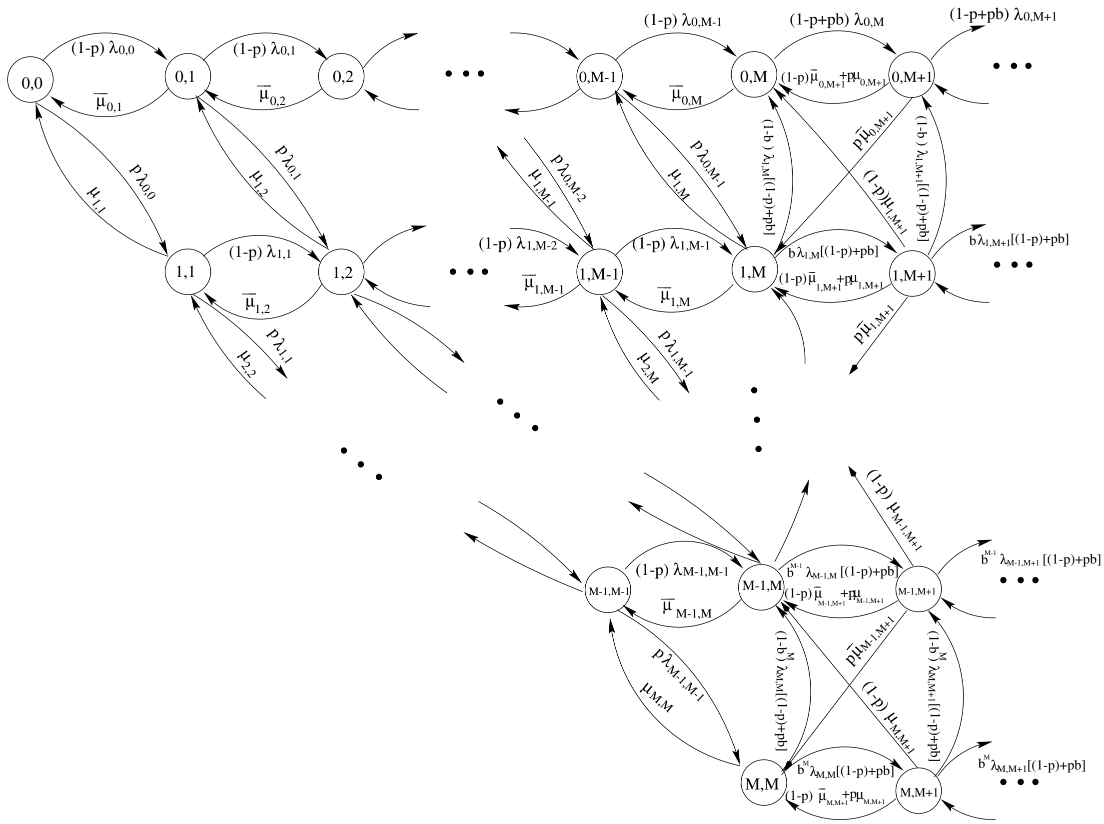

Fig. 3. State diagram for secondary relaying in a cell X.

$0 < i = j < M$:

$$(\mu_{j,j} + \lambda_{j,j}) \cdot Q(j,j) - p \cdot \lambda_{j-1,j-1} \cdot Q(j-1, j-1) \\ -\bar{\mu}_{j,j+1} \cdot Q(j, j+1) - \mu_{j+1,j+1} \cdot Q(j+1, j+1) = 0 \quad (18)$$

$0 < i \leq j < M$:

$$(\mu_{i,j} + \bar{\mu}_{i,j} + \lambda_{i,j}) \cdot Q(i,j) - p \cdot \lambda_{i-1,j-1} \cdot \\ Q(i-1, j-1) - (1-p) \cdot \lambda_{i,j-1} \cdot Q(i, j-1) - \bar{\mu}_{i,j+1} \\ \cdot Q(i, j+1) - \mu_{i+1,j+1} \cdot Q(i+1, j+1) = 0 \quad (19)$$

In addition,

$$\sum_{i=0}^{M} \sum_{j=0}^{\infty} Q(i,j) = 1 \quad (20)$$

Similar to the case for primary relaying, we assume (1) the probability of a new call coming is independent of the number of busy source, i.e. $\lambda_{i,j} = \lambda$; (2) the death rate is proportional to the number of busy sources, i.e., $\mu_{i,j} = i\mu$, and $\bar{\mu}_{i,j} = (j-i)\mu$ if $j < M$, or $\bar{\mu}_{i,j} = (M-i)\mu$ if $j \geq M$. By Plugging these values into Equations 10 through 20 and solving them, we get $Q(i,j)$ for $0 \leq i \leq j$. Then, we can compute the probability of $j - M$ or less calls terminating during the time t ($P_j(t)$) by using Equation 7. Thus, the probability of delay exceeding t for an incoming call is given by

$$W_s(t) = \sum_{i=0}^{M} \sum_{j=M}^{\infty} Q(i,j) P_j(t) \quad (21)$$

Accordingly, the average waiting time of an incoming call can be computed by

$$\overline{W}_s = \int_0^{\infty} t W_s(t) dt \quad (22)$$

As it is difficult to obtain a close-form expression for $W_p(t)$, $W_s(t)$, $\overline{W}_s$, and $\overline{W}_s$, we compute them numerically, and the results are presented in the next section.

IV. Results

In this section, we present the numeric results of new call delay in iCAR, by plugging in reasonable values of parameters in Equations 1 through 22. More specifically, we consider a cell A with traffic intensity T_A and six neighboring (tier B) cells with the same traffic intensity $T_B = 0.8T_A$. There are $M = 50$ DCHs in each cell. We assume one ARS is placed at each shared border of cell A and its neighboring cell (i.e., a tier B cell) . The cell radius is $2Km$, and the ARS transmission range is $500m$, which results in an ARS coverage of $p = 0.23$.

In order to make a fair comparison, we assume there are 7 additional channels † available either for the use as DCHs in the conventional cellular system or for relaying as in iCAR. In this research, we consider a cellular structure with channel reuse factor 7. To satisfy the co-channel interference constraint

†Previous simulation [8] has show that 3 relaying channels are sufficient for an iCAR system under normal operation range. In other words, the iCAR system with 3 or more relaying channels has a similar performance to that with unlimited relaying bandwidth when the traffic intensity is not too high.

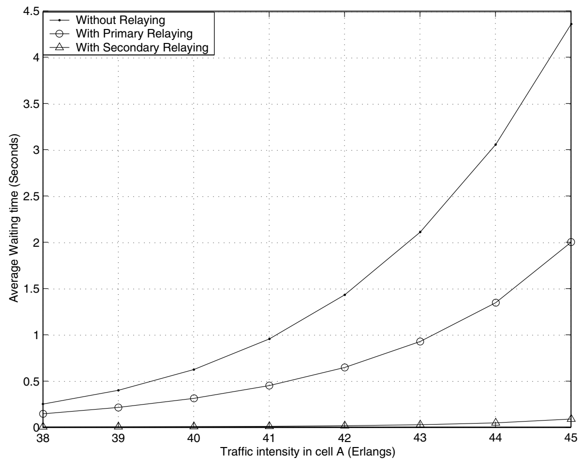

Fig. 4. Average new call delay.

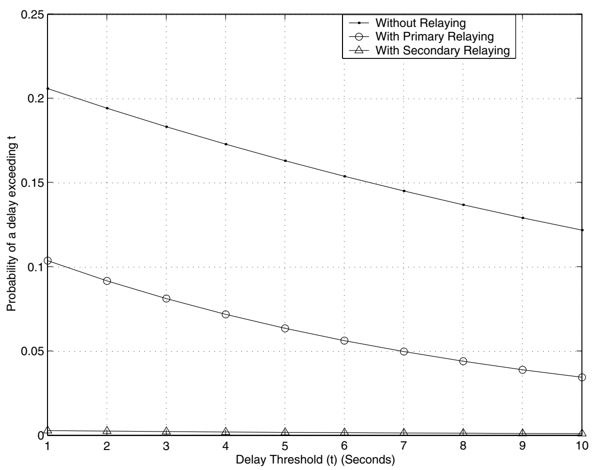

Fig. 5. Delay probability v.s. delay time t. $T_A = 43\ Erlangs$.

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 DCHs.

Fig. 4 shows the average delay of a call in the iCAR system. Observe that the queuing delay increases with the traffic intensity. The primary relaying can reduce the average new call delay, while the secondary relaying can reduce it further to no longer than $0.1\ seconds$. Similarly, as shown in Fig. 5 and Fig. 6, the primary and secondary relaying significantly reduce the probability that a new call experiences a delay exceeding a given time t, under various traffic intensities and t values. Note that, the delay introduced by establishing relaying path can be similar or less than the handoff delay in the cellular system (normally not exceeding $150ms$), which is much less than the queuing delay of the new calls in the cellular system, and thus is ignored.

V. Conclusion

We have presented an analytic model for the queuing delay performance of iCAR. Our analysis is based on the Markov chain model. The results show that the iCAR system with a limited ARS coverage and the comparable amount of bandwidth

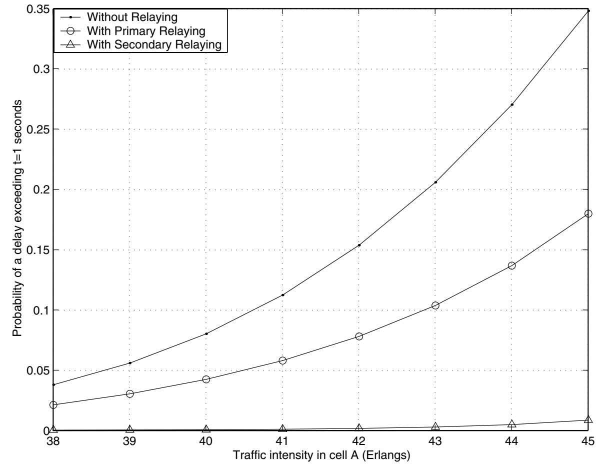

Fig. 6. Delay probability v.s. traffic intensity.

resource has a significantly lower call delay than that of a conventional cellular system. We also expect the analytical model developed here to be applicable to or provide guideline for the next generation heterogeneous wireless systems.

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