Dynamic Load Balancing and Sharing Performance of Integrated Wireless Networks

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***Abstract*—The capacity of wireless networks can be increased via dynamic load balancing/sharing by employing overlay networks on top of the existing cellular networks. One such recently proposed system is the integrated cellular and ad hoc relay (iCAR) system, where an overlay ad hoc network is employed to use the resources efficiently by dynamically balancing the load of the *hot spots* in the cellular network, and to provide quality-of-service to subscribers, no matter where they are located and when the request is made. It is assumed that this overlay network operates in the 2.4-GHz Industrial, Scientific, and Medical (ISM) band and, hence, the number of available ISM-band relay channels used for load balancing will be limited due to other users' interference at a given point in time. In this paper, the impact of ISM-band interference on the performance of iCAR systems, which is a representative hybrid wireless network, is studied, and it is shown that dynamic load balancing and sharing capabilities of iCAR systems are strictly dependent on the availability of the ISM-band relay channels. In addition to quantifying the impact of the number of available relay channels on the performance of iCAR systems, a simple channel assignment scheme to reduce the performance degradation due to other users' interference is also provided. Results show that this interference avoidance technique can improve the realistic performance of iCAR-like hybrid wireless networks by 12%–23% when the interferers are uniformly distributed in the ISM-band.**

***Index Terms*—Cellular networks, dynamic load balancing, interference, load sharing, performance analysis.**

I. INTRODUCTION

THE next-generation communication systems will involve widespread deployment of wireless networks. The aim is to provide high data-rates to mobile users in large coverage areas. However, since the bandwidth is limited, efficient allocation of resources (channels) to each cell in a wireless network is crucial for providing quality-of-service (QoS) to the subscribers requesting service. This problem becomes even more acute when some cells [e.g., access points in IEEE 802.11 wireless local area networks (LANs)] in the system are *congested* or *hot*, i.e., the traffic generated by the subscribers is more than the capacity of the service provider's infrastructure. This means that the grade-of-service (GoS) in those cells may go down to a level below a prescribed threshold (e.g., in a cellular system, the call blocking probability in congested cells goes above 2%). This localized congestion might result in a significant number of requests being blocked or dropped, even though the overall traffic load of the system has not reached its maximum threshold. This degradation in service quality is clearly not acceptable for wireless customers.

In cellular networks, one solution to the *hot spot* problem is dynamically balancing the load of the *hot* cells, i.e., handling of the excess traffic of the *hot* cells by the *cooler* cells in the network. Several researchers have previously proposed interesting dynamic load balancing and channel assignment schemes to overcome the *congestion* problem [1]–[15]. A common problem with most of the existing dynamic load balancing and channel assignment schemes is the fact that their use increases cochannel interference in the cellular network. A new approach recently proposed to solve the *hot spot* problem is employing overlay networks on top of the existing infrastructure: Integrated cellular and ad hoc relay (iCAR) system [16]. iCAR employs an *overlay ad hoc network* on top of a cellular network and makes use of the existing cellular infrastructure and modern ad hoc relay technologies (such as sensor networks), i.e., iCAR employs ad hoc relay stations (ARSs) within the cellular network to balance traffic loads efficiently and to share channels between congested and noncongested cells via primary and secondary relaying. These ARSs can operate in the Industrial, Scientific, and Medical (ISM) band (say at 2.4 GHz) and, therefore, do not cause interference to the cellular band [16]–[19]. Conceptually speaking, iCAR systems represent a *transitional scheme* between legacy cellular networks and future ad hoc wireless networks.

The performance of iCAR system was previously reported assuming that there is a sufficiently large number of relay channels and it was shown that under this assumption the call blocking probability in the *hot* cells could be decreased substantially [16]. While this provided valuable insight into the ultimate capability of iCAR, it is clear that the number of ISM-band channels at a given point in time will be limited due to interference from other users (such as Bluetooth or IEEE 802.11b users, microwave ovens, etc.) in the unlicensed spectrum. Lack of sufficient number of ad hoc relay channels due to other users' interference in the ISM-band could have serious performance implications in iCAR systems. In this paper, we use a *new approach* to quantify the interference-limited performance of iCAR systems in terms of the main system parameters including the number of ISM-band relay channels. Moreover, a simple illustration is provided on how the other users' interference in the ISM-band might degrade the performance of iCAR in terms of bit-error rate (BER) and required carrier-to-interference (C/I) ratio, and how this degradation

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can be reduced using a simple channel selection scheme. It is shown that the realistic performance of iCAR in terms of dynamic load balancing and load sharing is heavily dependent upon the number of available ISM-band relay channels, and the number of available relay channels will be determined by the amount of interference the ARSs will experience. Our results also indicate that the number of relay channels required for dynamic load balancing in iCAR is much more than the number of relay channels required for load sharing (i.e., for bringing the call blocking probability of the *hot spot* to 2%). Although, in this paper, we focus on the performance analysis of an iCAR system with voice communications, it is anticipated that the performance (e.g., in terms of throughput) of a wireless data network with centralized control [e.g., wireless local area networks (WLAN)] can be improved by relaying users from overloaded access points to lightly or moderately loaded access points. Similar to the call blocking probability, which is the performance metric used in this paper, the improvement that can be achieved in the throughput of a WLAN when ARSs are employed will depend on the level of interference experienced in the ISM-band. Furthermore, in a recent study [20], we have shown that several important dynamic load balancing schemes proposed in the literature, such as simple borrowing [6], channel borrowing without locking [8], directed retry [10], etc., could be studied using the developed analytical framework. Hence, it is anticipated that the ideas and analytical results of our study can also be applied to wireless data networks. Our current focus is on mapping the analytical tool developed for voice communications to wireless data networks.

The remainder of this paper is organized as follows. Section II gives an overview of the iCAR system. Analyses for primary and secondary relaying in iCAR systems are presented in Section III. The results are given in Section IV. An illustration of the ISM-band issues is provided in Section V. A simple interference avoidance scheme is described in Section VI. Finally, Section VII concludes the paper, while some of the details of the analytical derivations are relegated to the Appendix.

II. OVERVIEW OF iCAR SYSTEMS

The basic idea of an iCAR system is to place a number of ARSs throughout the geographical coverage area, so that the signals between the mobile hosts (MHs) and base transceiver stations (BTSs) can be relayed [16].[1] An ARS is a wireless communication device, which may have limited mobility under control of a mobile switching center (MSC), and it can communicate directly with an MH, a BTS, or another ARS through air interfaces. Each ARS has two air interfaces, one for communicating with the BTS (cellular interface) and the other for communicating with the MH and other ARS's (relay interface). ARSs might either use two separate ISM-band relay channels, or one relay channel at different time slots or with different codes, while communicating with each other. Similarly, each MH is assumed to have two air interfaces. It was shown before that the ARSs can operate in 2.4-GHz unlicensed ISM-band. Although the interference in the ISM-band due to the other users will limit the capacity of the ARSs, since they use a separate band from the cellular network, they will not cause any interference to the cellular band [16], [17]. Therefore, the cochannel interference faced by other dynamic load balancing and channel assignment schemes will not limit the performance of iCAR systems.

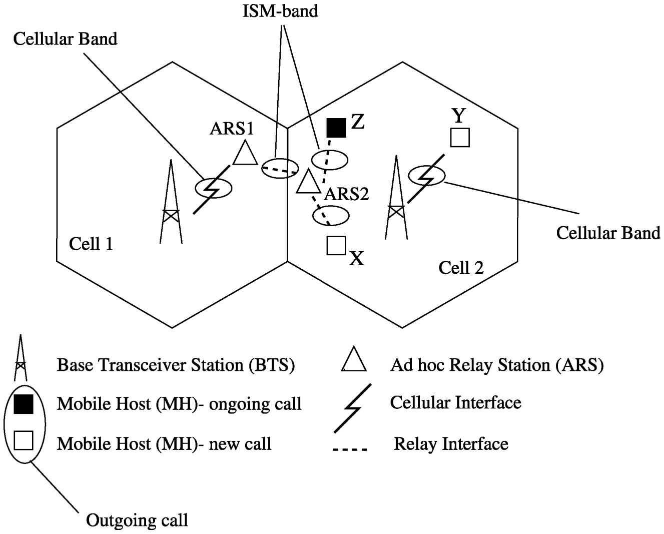

Fig. 1. Two-cell system layout investigated. Both primary relaying (user X) and secondary relaying (user Y via user Z) are illustrated.

In present cellular systems, if an MH is involved in a new call in a congested cell and is unable to find a channel (voice or data), the new call will be blocked, unless a load balancing strategy is incorporated. However, in an iCAR system, the request may still be honored. The types of relaying through ARSs can be described as follows.

- *Primary relaying*: If an MH cannot be assigned a channel in a congested cell, it can be *directly* relayed to a neighboring cell via ARSs if the MH is within the ARS coverage area [16], [17]. For example, assuming that cell 2 in Fig. 1 is congested, a new user X will not be able to find a cellular-band channel in cell 2. However, since it is in the coverage area of ARS2, it can use a channel of cell 1 via *primary relaying* through ARS2.
- *Secondary relaying*: If the MH requesting service is outside the ARS coverage area of the congested cell, an ongoing call within the ARS coverage can be relayed to a neighboring cell via ARSs freeing up a channel in the congested cell to serve the new call [16], [17]. Note that, when secondary relaying is employed, it is implied that primary relaying is also employed. For example, in Fig. 1, a new user Y cannot be assigned a channel in cell 2 and it is not covered by an ARS. In this case, checking if there are any ongoing calls within the ARS coverage area, one realizes that user Z is in the coverage area of ARS2. User Z is then relayed to cell 1, and user Y can then use the channel released by user Z in cell 2.

The timing diagrams for primary and secondary relaying of MH X and MH Z via the ARSs 1 and 2 are shown in Figs. 2 and 3, respectively. We will explain the primary relaying mechanism first. When MH X requests a channel from BTS2, BTS2 lets MH X know that there are no channels available at that time. Then,

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[1] Note that the MHs can be cellular subscribers, WLAN users, and the BTSs can be base stations, access points, etc.

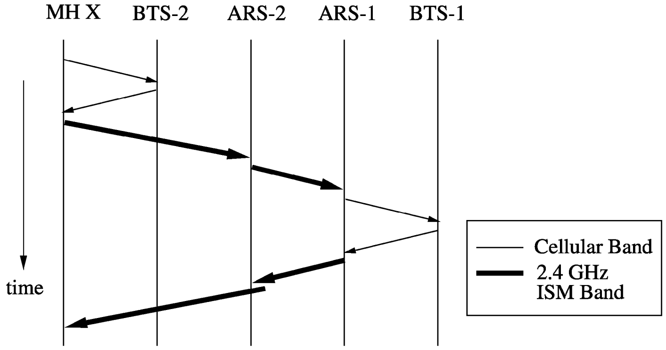


Fig. 2. Timing diagram for primary relaying.

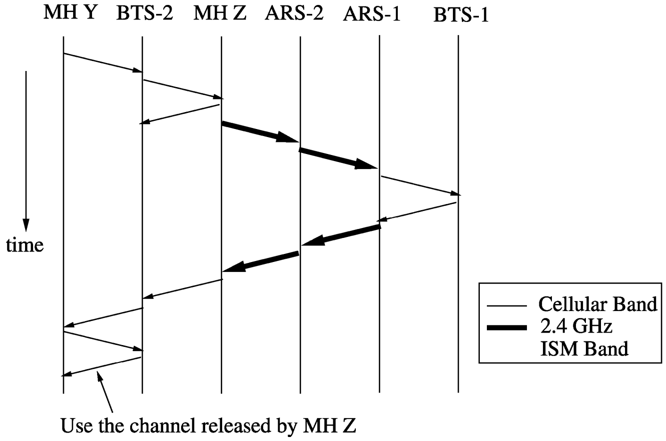


Fig. 3. Timing diagram for secondary relaying.

MH X switches to its relay interface and starts communicating with ARS2 through the ISM-band. A relaying route from MH X to BTS1 will then be formed through ARS2 and ARS1. After a channel is assigned to ARS1 by BTS1, the communication will start. MH X and ARS2 will use ISM-band to communicate, whereas ARS1 will use both cellular and ISM-band to communicate with BTS1 and ARS2, respectively.

When MH Y requests a channel from BTS2, BTS2 lets MH Y know that there are no channels available at that time (see Fig. 3). However, in this case, since MH Y is not within the ARS coverage area, BTS2 asks MH Z to switch to its relay interface and start communicating with ARS2 through an ISM-band relay channel. The cellular-band channel released by MH Z is then assigned to MH Y. Note that, although not shown in the timing diagrams, call setup will be established under the supervision of MSC.

III. ANALYSIS OF iCAR WITH FINITE NUMBER OF ISM-BAND RELAY CHANNELS

In previous works, the load-balancing capability and the performance of iCAR was studied with the key assumption that the number of relay channels is sufficient, i.e., the system parameters that were taken into consideration were the traffic intensities, the number of cellular-band channels, and the coverage area of the ARSs [16], [17], [19]. Therefore, it was assumed that if a MH were in the coverage area of an ARS, it could be relayed to any nearby *cool* cell. However, to be able to analyze the realistic performance of iCAR, the impact of the number of ISM-band relay channels and the availability of these channels should be studied. To this end, in this paper, we provide closed-form expressions to quantify the performance of iCAR in terms of the main system parameters including the number of available ISM-band relay channels.

To analyze the performance of iCAR in a multitier coverage area (see, for example, the three-tier system in [16]) with limited number of relay channels one needs to use a multidimensional Markov-chain analysis. Unfortunately, the complexity of such analysis increases exponentially with the number of cells (and number of tiers). Therefore, to gain insight, the scenario under investigation is first modeled as a simple two-cell system (see Fig. 1) and is analyzed via a four-dimensional (4-D) Markov chain [21], [22]. However, in [23], it is shown that the two-cell system can be generalized to more realistic multitier coverage areas with multiple *hot spots* with arbitrary locations.

In the analysis, we assume that call requests arrive according to a Poisson process and call arrival rates in cells 1 and 2 are λ_1 and λ_2, respectively; and service times are exponentially distributed with parameter μ (i.e., call termination rate in both cells is μ). Hence, one can use a Markov chain to analyze the performance of iCAR systems [24]. It is also assumed that each cell in the system has M cellular-band channels and K ISM-band relay channels, where $M > K$. The ARSs are located across the shared border of the two cells. The ARS coverage area is normalized with respect to the base station coverage area and is denoted by p. For simplicity, we assume that the users are uniformly distributed throughout a cell. The parameters used in the analysis are summarized in Table I. Note that the analysis presented in this paper does not incorporate issues related to handoff, routing, mobility of the ARSs, the transceiver design in the ARSs, etc. These issues will be addressed in future studies.

When employing iCAR, our objective is to increase the capacity of the congested cell without decreasing the capacity of the neighboring cells. We therefore assume that whenever a call using a cellular-band channel is terminated in a congested cell, one of the relay channel users (if such a user exists) will be switched to the available cellular-band channel, and the corresponding relay channel will be released. This way unnecessary usage of the resources and, hence, a degradation in the capacity of the neighboring cell can be avoided.

A. Analysis of Primary Relaying

In the following, we provide closed-form expressions for the new call blocking probability when *only* primary relaying is employed in an iCAR system. These closed-form expressions are obtained by solving the state-flow equations of a two-dimensional (2-D) Markov chain. A brief outline of the analysis is given in the Appendix. Further details of this analysis can be found in [18] and [21]. The call blocking probability of cell 1 will be given. The call blocking probability for cell 2 can be calculated similarly. First, we will determine the blocking events.

TABLE I
SYSTEM PARAMETERS USED IN THE ANALYSIS

Notation	**Definition**
M	Number of cellular-band channels
K	Number of ISM-band relay channels
p	Normalized ARS coverage with respect to cellular area
λ_1, λ_2	Call generation rate in cells 1 and 2
μ	Call termination rate in cells 1 and 2
$T_1 = \frac{\lambda_1}{\mu}$, $T_2 = \frac{\lambda_2}{\mu}$	Traffic intensities in cells 1 and 2
i_1, i_2	Number of active MH's (including cellular and ISM-band users) in cells 1 and 2
j_1, j_2	Number of active MH's within the ARS coverage area in cells 1 and 2

1) A new call in cell 1 will be blocked with probability 1, if:
    a) all relay and cellular-band channels in cell 1 are being used;
    b) all $2M$ cellular-band channels in cells 1 and 2 are being used.
2) A new call in cell 1 will be blocked with probability $(1-p)$, if all cellular-band channels in cell 1 are being used and the MH requesting service is not within the ARS coverage area.

Using these facts one can show that the call blocking probability in cell 1, denoted by P_{B_P}, is given as [21]:

$$\begin{aligned} P_{B_P} = S(0;0) \Bigg\{ & \frac{T_1^{M+K} p^K}{(M+K)!} \sum_{i_2=0}^{M-K} \frac{T_2^{i_2}}{i_2!} \\ & + T_1^{2M} \sum_{i_2=M+1}^{M+K} \left(\frac{T_2}{T_1}\right)^{i_2} \frac{p^{i_2-M}}{i_2!(2M-i_2)!} \\ & + T_2^{2M} \sum_{i_1=M}^{M+K-1} \left(\frac{T_1}{T_2}\right)^{i_1} \frac{p^{i_1-M}}{i_1!(2M-i_1)!} \\ & + \sum_{i_1=M}^{M+K-1} \frac{T_1^{i_1}(1-p)p^{i_1-M}}{i_1!} \sum_{i_2=0}^{2M-i_1-1} \frac{T_2^{i_2}}{i_2!} \Bigg\} \end{aligned} \quad (1)$$

where $T_1 = \lambda_1/\mu$ and $T_2 = \lambda_2/\mu$ are the traffic intensities of cells 1 and 2, respectively, and $S(0;0)$ is the idle-state probability and is given by

$$\begin{aligned} S(0;0) = \Bigg\{ & \sum_{i_1=0}^{M} \sum_{i_2=0}^{M} \frac{T_1^{i_1} T_2^{i_2}}{i_1! i_2!} \\ & + \sum_{i_1=M+1}^{M+K} \sum_{i_2=0}^{2M-i_1} \left\{ T_1^{i_1} T_2^{i_2} + T_2^{i_1} T_1^{i_2} \right\} \frac{p^{i_1-M}}{i_1! i_2!} \Bigg\}^{-1}. \end{aligned} \quad (2)$$

Physically, the first three terms in (1) correspond to complete blocking states, i.e., all available channels in cells 1 and 2 are being used, while the last term corresponds to the states where primary relaying cannot be done, although there are available channels in cell 2.

B. Analysis of Secondary Relaying

When secondary relaying is studied, one should keep track of the active users in the ARS coverage area. When the system is congested, if a new call is generated outside ARS coverage area, one cannot do primary relaying (see Fig. 1). Therefore, one needs to find an active user in the ARS coverage area, and switch that user to relay interface and assign the channel released by that user to the user requesting service. Hence, the states for the secondary relaying are chosen to be of the form $S(i_1, i_2; j_1, j_2)$, where i_1 and i_2 are the total number of active users, and j_1 and j_2 are the number of active users within the ARS coverage area in cells 1 and 2, respectively. Note that secondary relaying is employed if and only if primary relaying does not work, i.e., the user requesting service is not within the ARS coverage area.

Proceeding in a similar way with the analysis of primary relaying, one can find the state probabilities and the call blocking probabilities by solving the state-flow equations of the 4-D Markov chain analysis (the details can be found in [21] and [22]). Below, the call blocking probability of cell 1 will be provided. The call blocking probability for cell 2 can be calculated similarly. First, we will determine the blocking events.

1) A new call in cell 1 will be blocked with probability 1, if:
    a) all relay and cellular-band channels in cell 1 are being used;
    b) all $2M$ cellular-band channels in cells 1 and 2 are being used.
2) A new call in cell 1 will be blocked with probability $(1-p)$, if all cellular-band channels in cell 1 are being used and there are no ongoing calls within the ARS coverage area to employ secondary relaying.

Using these facts, one can show that the call blocking probability in cell 1 when secondary relaying is employed, denoted by P_B, is given as [22]:

$$\begin{aligned} P_B = {} & S(0,0;0,0) \\ & \cdot \Bigg\{ T_1^{M+K} \sum_{i_2=0}^{M-K} \frac{T_2^{i_2}}{i_2!} \sum_{j_1=K}^{M+K} \frac{p^{j_1}(1-p)^{M+K-j_1}}{j_1!(M+K-j_1)!} \\ & + \sum_{i_2=M+1}^{M+K} \sum_{j_2=i_2-M}^{i_2} \left(\frac{T_2}{T_1}\right)^{i_2} \frac{T_1^{2M} p^{j_2}(1-p)^{i_2-j_2}}{j_2!(i_2-j_2)!(2M-i_2)!} \\ & + \sum_{i_1=M}^{M+K-1} \sum_{j_1=i_1-M}^{i_1} \left(\frac{T_1}{T_2}\right)^{i_1} \frac{T_2^{2M} p^{j_1}(1-p)^{i_1-j_1}}{j_1!(i_1-j_1)!(2M-i_1)!} \\ & + \sum_{i_1=M}^{M+K-1} \frac{T_1^{i_1} p^{i_1-M}(1-p)^{M+1}}{M!(i_1-M)!} \sum_{i_2=0}^{2M-i_1-1} \frac{T_2^{i_2}}{i_2!} \Bigg\} \end{aligned} \quad (3)$$

where T_1 and T_2 are the traffic intensities of cells 1 and 2, respectively, p is the normalized ARS coverage (normalized with respect to the coverage area of one cell), M is the number of cellular-band channels and K is the number of ISM-band relay channels, and $S(0,0;0,0)$ is the idle-state probability and is given by

$$S(0,0;0,0) = \left\{ \sum_{i_1=0}^{M} \sum_{i_2=0}^{M} \frac{T_1^{i_1} T_2^{i_2}}{i_1! i_2!} + \sum_{i_1=M+1}^{M+K} \sum_{i_2=0}^{2M-i_1} \sum_{j_1=i_1-M}^{i_1} \frac{\left(T_1^{i_1} T_2^{i_2} + T_2^{i_1} T_1^{i_2}\right)(1-p)^{i_1-j_1} p^{j_1}}{i_2! j_1! (i_1-j_1)!} \right\}^{-1}. \quad (4)$$

Equation (3) gives call blocking probability of a congested cell in terms of main system parameters such as traffic intensity of the congested cell, the number of channels available in the cellular and ISM-band, and the coverage area of the relay stations. The first three terms in (3) physically correspond to complete blocking states, i.e., all available channels in cells 1 and 2 (including the ISM-band relay channels) are being used, and the last term corresponds to the states where secondary relaying cannot be done, although there are available cellular-band channels in cell 2.

Observe that when there is *negligible coverage by ARSs and no ISM-band relay channels*, i.e., when $p = 0$ and $K = 0$, (3) reduces to

$$P_B = \frac{\frac{T_1^M}{M!}}{\sum_{i=0}^{M} \frac{T_1^i}{i!}} \quad (5)$$

which is the well-known *Erlang B* formula [1]. This is an important sanity check for the validity of the complex analysis conducted for obtaining the closed-form result given in (3).

IV. RESULTS AND DISCUSSIONS

In this section, we will study the load balancing and sharing performance of iCAR systems with a limited number of ISM-band relay channels, for a two-cell system.

The system under investigation is the two-cell system shown in Fig. 1 with traffic intensities of $T_1 = 50$ and $T_2 = 30$ Erlangs and with number of cellular-band channels $M = 50$. The call blocking probabilities corresponding to these traffic intensities are 10% and 0.02%, respectively.

We first study *the effect of the number of relay channels* (K) *on the performance of this system*, when the ARS coverage p is fixed. Fig. 4 shows the effect of K on the call blocking probabilities for $p = 0.3$, when primary and secondary relaying is employed. Observe that, when only primary relaying is employed, the call blocking probability of cell 1 does not decrease substantially, and it remains higher than 2%. However, when secondary relaying is also employed, for $K > 10$ the call blocking probability of the *hot* cell drops below 2%, whereas the call blocking probability of cell 2 (see the curves with ○ and ●) is still low. When K is further increased, Fig. 4 shows that call blocking probability reaches its minimum, which is 0.5% for these specific parameter values.

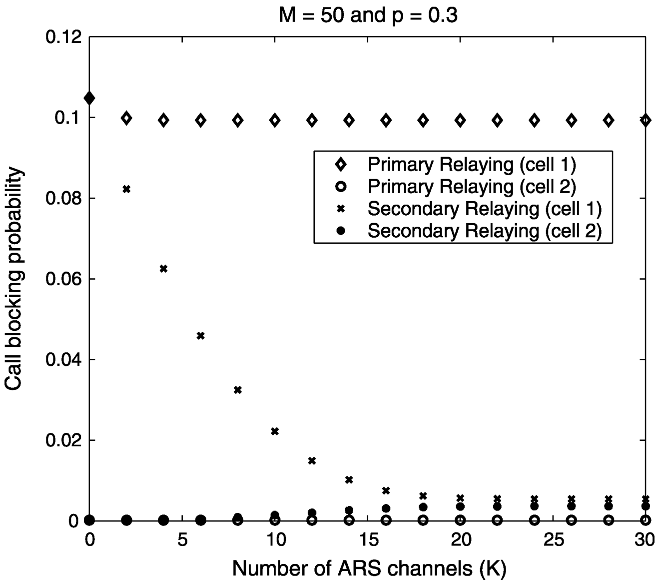


Fig. 4. Call blocking probabilities of cells 1 and 2 with primary and secondary relaying versus number of ISM-band relay channels K, when $M = 50, p = 0.3$, $T_1 = 50$, and $T_2 = 30$ Erlangs.

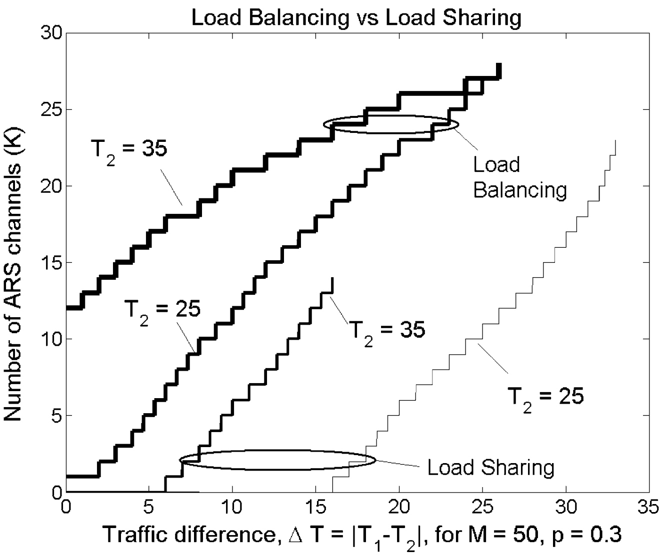


Fig. 5. Minimum number of relay channels required to achieve a call blocking probability less than 2% (i.e., load sharing) and to achieve load balancing versus the traffic intensity difference between cells 1 and 2 for $M = 50$ and $p = 0.3$.

Next, we study *the impact of the traffic intensities in cells 1 and 2 on the number of relay channels required to achieve a GoS of 2% and to achieve load balancing* in the *hot* cell. The number of cellular-band channels in each cell is assumed to be 50 and the normalized ARS coverage (normalized with respect to one cell's coverage area) is assumed to be 0.3.

Fig. 5 shows the relation between the traffic intensity difference between the two cells, i.e., $\Delta T = T_1 - T_2$, and the minimum number of relay channels required to achieve 2% call blocking probability (we call this *load sharing* in this paper) and *perfect load balancing* (indicated with thick legends) in cell 1, when the traffic intensity of cell 2 is kept fixed (i.e., for a fixed T_2 value). Observe that for load sharing, traffic transfer does not begin till the call blocking probability of cell 1 exceeds

2%, which happens when T_1 exceeds 40 Erlangs [e.g., when $T_2 = 25$ Erlangs, no load balancing occurs till $T_1 = 41$ Erlangs (i.e., till $\Delta T = 16$ Erlangs)].

The minimum number of relay channels required, as expected, increases as ΔT is increased. For example, when $T_2 = 25$ Erlangs, while for $T_1 = 45$ Erlangs, five relay channels would suffice for forcing the call blocking probability of cell 1 to 2%, the number of relay channels required for $T_1 = 55$ Erlangs for 2% call blocking probability would go up to 17. Observe that for a fixed excess traffic (i.e., ΔT), the number of relay channels required for load sharing increases when T_2 (i.e., the traffic intensity of the *cooler* cell) increases. For example, for an excess traffic of 12 Erlangs, whereas the number of required relay channels is 0 when $T_2 = 25$ Erlangs, it is 8 when $T_2 = 35$ Erlangs. After a certain threshold (saturation point), since the system reaches its maximum capacity, call blocking probability cannot be decreased below 2% even if K is increased. For example, the system would not be able to sustain an acceptable GoS (i.e., 2% call blocking probability) if T_1 becomes larger than 58 Erlangs when $T_2 = 25$ Erlangs (i.e., for $\Delta T \geq 33$ Erlangs). Therefore, the number of required relay channels depends not only on the amount of excess traffic, but also on the amount of total traffic in the system.

Observe from Fig. 5 that the minimum number of relay channels necessary for *perfect load balancing* is always higher than the number of relay channels required for achieving 2% call blocking probability (i.e., load sharing). This is the case since all relayable excess traffic of the *hot* cell needs to be transferred to a *cooler* cell to achieve load balancing, whereas only a portion of the maximum relayable traffic needs to be transferred to achieve load sharing. For example, whereas the number of relay channels required for load sharing (i.e., for achieving 2% call blocking probability) is 5 when $T_2 = 35$ Erlangs and $T_1 = 45$ Erlangs, for perfect load balancing the number of relay channels required is 20 for the same traffic intensities in the two-cell system studied in this paper. Note that, although for some cases (e.g., when the total traffic intensity in the system exceeds the system capacity) call blocking probability cannot be decreased below 2%, it can still be decreased substantially by load balancing.

Fig. 5 clearly shows that the load balancing and load sharing capabilities of iCAR system strongly depend on the number of available relay channels. For a given excess traffic (i.e., $T_1 - T_2$), the requirements for dynamic load balancing are much more stringent than those for load sharing (i.e., pulling the call blocking probability of the *hot spot* to 2%). Thus, in future unlicensed ISM-band operations, the availability of a sufficient number of ISM-band relay channels could determine the extent of load balancing or sharing one can achieve with iCAR systems.

Next, we study *the effect of the normalized ARS coverage* p on the call blocking probabilities of cells 1 and 2. Fig. 6 shows the relation between the ARS coverage p and call blocking probabilities for $K = 15$, when primary and secondary relaying is employed. As p is increased, the call blocking probability of cell 1 drops for both cases. With only primary relaying, call blocking probability of cell 1 drops below 2% for very high ARS coverage, which may be difficult and expensive to provide, whereas with secondary relaying this call blocking probability can be decreased below 2% for a normalized ARS coverage of 0.2. Note that, for this system, cell 1 can support up to 54 Erlangs of traffic with a resulting call blocking probability less than 2%. Therefore, with iCAR, one can utilize the unused resources (channels) of the other cells in the system and increase the capacity of the *hot* cells.

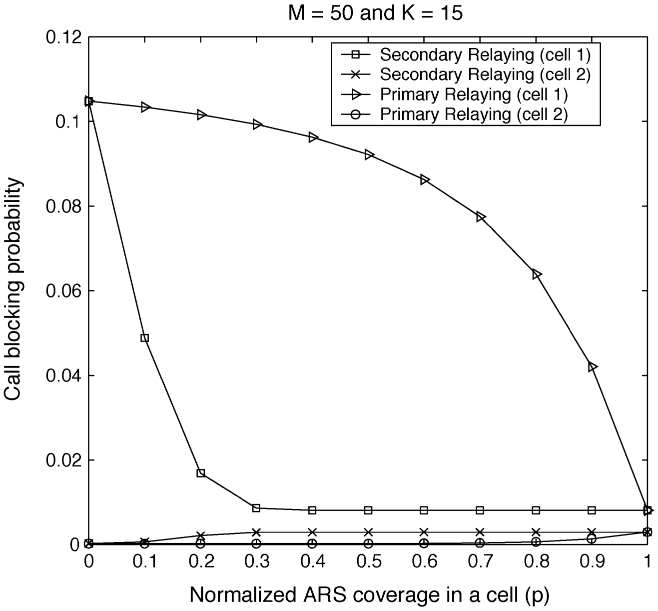


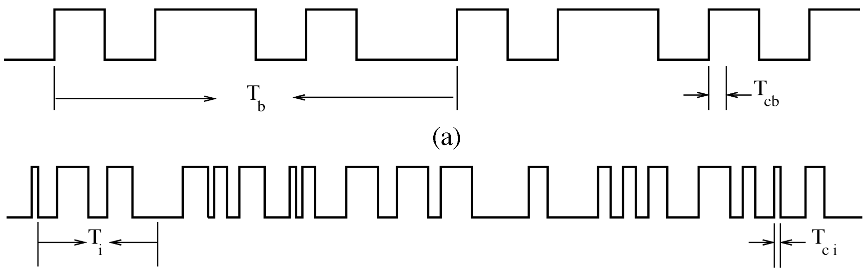
Fig. 6. Call blocking probabilities of cells 1 and 2 with primary and secondary relaying versus normalized ARS coverage, p, when $M = 50, K = 15, T_1 = 50$, and $T_2 = 30$ Erlangs.

Note that the transmitted power, hence the coverage area, of ARSs is also limited due to ISM-band regulations. One needs to increase the transmitted power of each ARS to have a small number of ARSs within cellular coverage area. However, the interference that will be caused to other technologies operating in the ISM-band should also be taken into consideration when designing the ARSs. Therefore, not only the number of available relay channels, but the coverage area (i.e., transmitted power) of the ARSs will determine the level of load balancing and load sharing that can be achieved with iCAR systems.

While the results shown in Figs. 4–6 are based on the simple two-cell system shown in Fig. 1, we have verified that one can extend the developed closed-form expressions to more realistic multitier coverage areas with arbitrary number of congested cells (*hot spots*) that may have arbitrary locations in a given coverage area. For example, the analytical tool developed based on the two-cell system of Fig. 1 was applied to the three-tier coverage area studied in [16] and an excellent agreement was found between simulation results and the analytical results developed in this paper [23].

V. AN ILLUSTRATIVE EXAMPLE

Although, while performing the analysis, perfect channel conditions were considered, interference in the 2.4 GHz unlicensed ISM-band will affect the number of available ISM-band relay channels and, hence, the performance of iCAR systems.



(a)

(b)

Fig. 7. Signals from the (a) ARS and (b) WLAN user.

The primary (i.e., licensed) users of the ISM-band include the amateur radio, radiolocation, fixed microwave, etc., whereas the most important secondary (i.e., unlicensed) users are IEEE 802.11b WLAN and Bluetooth users, cordless phones, microwave ovens, industrial heating, etc., [26], [27]. In this section, we provide an illustrative example on how the number of ISM-band relay channels will be limited due to interference caused by the other users of the band. For this example, we assume that the main source of interference is the IEEE 802.11b WLAN users within the coverage area of the ARSs.

IEEE 802.11b WLAN technology employs direct-sequence spread spectrum (DSSS) with a processing gain of 10.4 dB (11 chips) and for the example, we consider a data rate of 1 Mb/s. The spread-signal occupies a bandwidth of 22 MHz and there are 11 DSSS carrier frequencies for use in the U.S. ranging from 2.412 to 2.462 GHz. While specifying the parameters such as the processing gain, data rate, etc., for the ARSs in this example, we followed the FCC rules (Title 47 of the Code for Regulations Part 15 [28]). We assume that the ARSs employ code-division multiple-access (CDMA) technology with processing gain of 128 (i.e., 21 dB which is larger than the 10-dB minimum processing gain required by FCC). The data rate is assumed to be 9600 b/s (we consider voice communication only for the cellular system); therefore, the chip rate is 1.2288 Mc/s. We also assume that both systems employ binary phase-shift keying (BPSK) modulation. Fig. 7 shows the signal from the interferer and the ARS.

In [29], an analysis and a closed-form expression is provided for the BER when a DSSS signal interferes with other DSSS signals. In the following, we will develop an approximate analysis for the BER and we will use that analysis to find the amount of interference that can be tolerated by the ARSs to have an acceptable voice quality. In [29], it was shown that the total contribution of interference during the signal period T_b could be found in terms of the interference during each chip period. We will make use of this result while developing our analysis. We will first find the interference caused to each chip and the total interference will be the sum of the interference from each chip period.

Comparing the chip periods of our signal (T_{cb}) and the interferers (T_{ci}), we realize that in one signal-chip period there can be at most $\lceil T_{cb}/T_{ci} \rceil$ interferer chips, where $\lceil \cdot \rceil$ denotes the ceiling function. We can treat each chip of the ARS signal as a despread signal and each chip of the interferers that fall into one ARS signal-chip period as a spread-signal with a processing gain of $\lceil T_{cb}/T_{ci} \rceil$. Therefore, the system (which consists of only one ARS-signal chip period) reduces to a CDMA system. Hence, one can use the expressions for the interference variance obtained for spread-spectrum CDMA [1] for this case. Note that the total interference is the *sum* of the interference from all interferers (which are independent from each other) in the system and using *central limit theorem* [30], one can approximate the distribution of the total interference by a Gaussian distribution. Since the ARS coverage area is large enough (i.e., the number of interferers within the ARS coverage area is high enough), one can conclude that the Gaussian approximation will be accurate.

The BER is given by the following [1]:

$$P_e = Q\left(\sqrt{\frac{P_0 T_b^2}{2\sigma^2}}\right) \tag{6}$$

$$\sigma^2 = \sigma_I^2 + \sigma_n^2 \tag{7}$$

where P_0 is the received signal power (from user of interest), T_b is the bit period, $\sigma_n^2 = N_0 T_b/4$ is the variance of the Gaussian noise process, and σ_I^2 is the variance of the interference process which will be calculated in the following, and the Q-function is defined as $Q(z) \triangleq \int_z^\infty (1/\sqrt{2\pi}) e^{-y^2/2} dy$.

After some algebra, the variance of the interference to one ARS signal chip period is found to be

$$\begin{aligned}\sigma_i^2 &= \frac{T_{cb}}{T_{ci}} \frac{N_i T_{ci}^2}{6} \sum_{k=1}^{L} \frac{P_k}{N_i} \\ &= \frac{T_{cb} T_{ci}}{6} \sum_{k=1}^{L} P_k\end{aligned} \tag{8}$$

where P_k is the power from the kth interferer, N_i is the processing gain for the interferers (i.e., WLAN users), and L is the total number of interferers. Therefore, the total interference to the ARS signal becomes

$$\begin{aligned}\sigma_I^2 &= N_b \sigma_i^2 \\ &= \frac{T_b T_i}{6 N_i} \sum_{k=1}^{L} P_k\end{aligned} \tag{9}$$

where N_b is the processing gain for the ARS users.

The BER for the ARS then becomes

$$\begin{aligned}P_e &= Q\left(\sqrt{\frac{P_0 T_b^2}{2\left(\sigma_I^2 + \sigma_n^2\right)}}\right) \\ &= Q\left(\sqrt{\frac{1}{\left(\frac{T_i}{3 T_b N_i} \frac{1}{\frac{C}{I}} + \frac{1}{\frac{2E_b}{N_0}}\right)}}\right)\end{aligned} \tag{10}$$

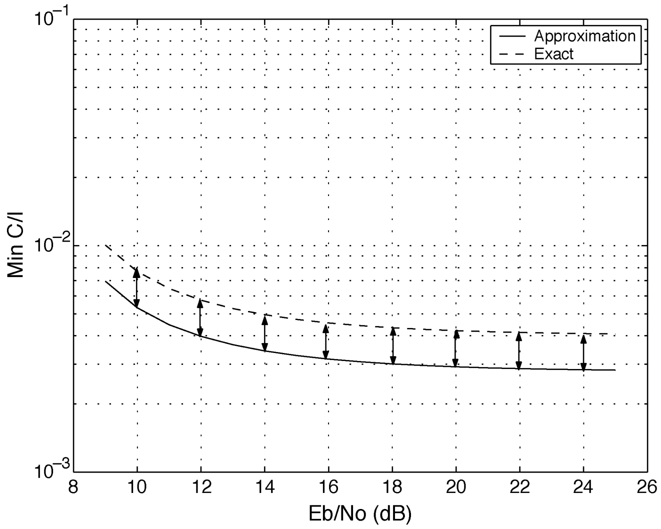


Fig. 8. Minimum required C/I for $P_{e_{\max}} = 10^{-3}$.

after substituting for σ_I^2 and σ_n^2, where $E_b = P_0 T_b$, and C/I is the carrier-to-interference ratio. Note that for a system with $T_b = T_i$ and $N_b = N_i = N$, if power control is employed (i.e., $P_k = P$) and if the number of users is L (i.e., total number of interferers is $L - 1$), then it is easy to show that (10) reduces to

$$P_e(\mathrm{CDMA}) = Q\left(\sqrt{\frac{1}{\left(\frac{L-1}{3N} + \frac{N_0}{2E_b}\right)}}\right) \tag{11}$$

which is the BER expression for a typical direct-sequence code-division multiple-access system [1].

If we assume that the maximum BER that can be tolerated for acceptable voice quality is $P_{e_{\max}}$, then the minimum required C/I can be calculated to be

$$\left(\frac{C}{I}\right)_{\min} = \frac{\frac{T_i}{3N_i T_b}}{\left(\frac{1}{(Q^{-1}(P_{e_{\max}}))^2} - \frac{N_0}{2E_b}\right)} \tag{12}$$

where $Q^{-1}(.)$ is the inverse Q-function. The *C/I* ratio will determine the number of interferers that can be tolerated. Also, it can provide useful insight as to where the ARSs can be located to avoid excessive interference to/from the already deployed WLANs.

Fig. 8 shows the minimum *C/I* ratio necessary to achieve a $P_{e_{\max}}$ of 10^{-3} for different *fixed* values of E_b/N_0. The exact results are calculated using the expressions developed in [29]. The approximate and exact results are in good agreement. Looking at the plot, we realize that for a typical E_b/N_0 value of 10 dB, a *C/I* ratio of -20 dB is sufficient for good voice quality.

Consider the following scenario. Suppose the traffic intensity of the *hot cell* is 55 Erlangs, which corresponds to a call blocking probability of 16%, and the traffic intensity of the neighboring cell is 25 Erlangs. Looking at Fig. 5, one can realize that for this scenario the call blocking probability of the *hot cell* can be reduced to less than 2%, when the number of available relay channels K is at least 16. Note that the spread signal will occupy a bandwidth of 1.25 MHz, and since the available bandwidth in the ISM-band is around 80 MHz, we have a sufficient number of relay channels for the ARS operation. Let us assume that each cell can reach 20 relay channels at a given time. The worst case will occur if the ARS and the WLAN users use the same carrier frequency (and the analysis in this section is performed for the worst case). Considering this case, as long as the signal power is at most 20 dB below the interference power, the voice quality will be acceptable.

The best case occurs when the (*C/I*) ratio in all 20 relay channels is higher than the minimum required (*C/I*) ratio and, hence, the number of available ISM-band relay channels in the congested cell is 20. Now, let us assume that the interference level is too high in 8 of these 20 relay channels (i.e., $C/I < (C/I)_{\min} = -20$ dB) due to the WLAN users within the ARS coverage area. In this case, the number of available relay channels drops to 12. From (3), the call blocking probability of the *hot cell* for this case can be calculated to be 4%, i.e., higher than 2%.

With this simple example, one can see that the performance of iCAR strictly depends on the number of available channels which is limited due to the other technologies' interference. Although employing spread-spectrum techniques will increase the resilience to noise, interference, jamming, and unauthorized detection, the impact of the interference from the other devices to ARSs can further be reduced by resorting to different methods. One method is to employ classical techniques to suppress interference such as modulation, channel coding, interleaving, and equalization [1]. The performance can also be improved by interference detection and estimation. These types of mechanisms can be either collaborative or noncollaborative [26], [31]. In collaborative schemes, priorities can be given to different technologies depending on the application they are running. The noncollaborative schemes can range from adaptive frequency selection, to scheduling and traffic control. With adaptive channel selection, the presence of other devices in the band can be detected by measuring, for instance, the BER, the signal strength, or the signal-to-interference ratio. Therefore, ARSs can be designed with interference suppression capability and if other users in some of the available frequencies are detected, the relayed users may be assigned channels such that the already occupied frequencies are not used or more sparingly used. However, while designing ARSs that will be used to relay the excess traffic of the *hot* cells, the complexity and cost of the ARSs should also be taken into account. Recall that an ARS is assumed to be a dual-band wireless device with limited mobility, whose main function is transmitting and receiving signals at two different (widely separated) carrier frequencies. Such radios (e.g., dual-band cordless phones that can operate in the 900 MHz and 2.4 GHz bands) have already been built [32]. Therefore, the ARSs can indeed be implemented using the existing technologies. In addition, ARSs should also be capable of switching between the two carrier frequencies, since the final ARS in the relay route will need to transmit and receive at two different carrier frequencies simultaneously (see ARS1 in Figs. 1–3).

VI. ISM-BAND INTERFERENCE SUPPRESSION/AVOIDANCE

As mentioned above, one can use interference suppression or avoidance techniques, to overcome the limitations due to the other technologies' interference in the ISM-band. Since, in this paper, we assume that ARSs employ CDMA technology, ARSs can be designed using interference suppression and multiuser detection methods proposed for CDMA systems, such as successive or parallel interference cancellation [33]–[35], etc. However, all of these schemes require high signal processing power and increase the complexity of the ARSs, which defeats the purpose of solving the *hot* spot problem *cost efficiently*. Therefore, instead of suppressing the interference from other users, we will try to reduce the impact of the interference on the performance of iCAR without requiring additional complexity in the design of ARSs. We only require the ARSs to measure the *C/I* ratio in the ISM-band relay channels.

We will provide a simple example, which illustrates a very simple channel assignment technique based on *C/I* ratio measurements, and we will compare the BER performance of a relayed user when a channel is randomly assigned to the user and when the best channel (in terms of interference level) is assigned to the user. The main system parameters such as the bit and chip rates, processing gain, etc., were given previously (see Section V). We assume that $E_b/N_0 = 10$ dB, and the transmitted powers of the ARS's and the WLAN users are the same. Hence, *C/I* ratio becomes the reciprocal of the number of interferers within the ARS coverage area. Since the ARSs require less data rate the range of the ARSs is larger than that of the WLAN devices and, therefore, there can be more than one IEEE 802.11b access point within an ARS coverage area.

We will study two different schemes.

1) *Random channel selection*, where any one of the free relay channels is randomly assigned to the relayed user with equal probability.
2) *Best channel selection*, where the free relay channel with the highest *C/I* ratio is assigned to the relayed user.

Since there are three nonoverlapping channels in the ISM-band for WLAN users, we assume that each ARS can reach at most three relay channels at a given point in time. The number of interferers using each channel is generated *randomly* following a uniform or normal distribution, and the best channel is assumed to be the one which is used by the smallest number of interferers. The results are generated using (10) provided in Section V. Fig. 9 shows the average BER a relayed user will experience versus the total number of interferers (who can use any of the three available ISM-band channels) within the ARS coverage area, when random and best channel selection methods are employed. As expected, best channel selection method performs better than random channel selection method. The improvement over random channel selection method in BER achieved by best channel selection method ranges from 12% to 23%, when the number of interferers is uniformly distributed through the three channels. When $P_e = 10^{-3}$, 550 interferers can be tolerated when random channel selection is employed, whereas 600 interferers can be tolerated if best channel is selected. The improvement becomes more significant, when the number of interferers per channel is normally distributed (which may make the number of interferers using one channel significantly higher than the number of interferers using the other channels). In this case, the improvement achieved by best channel selection ranges from 65% to 90%. Therefore, if the number of interferers per channel is not uniform, using the best channel selection method can improve the performance of an iCAR system substantially. The improvement can be further enhanced, if the channel assignment decision also takes into account the interference level at different ARS coverage areas (e.g., the number of interferers within the coverage area of some ARSs may be significantly lower than the others). This example provides a simple method to reduce the deleterious effect of the other users' interference on the performance of iCAR; however, further research is required to overcome the limitations due to the nature of ISM-band and to improve the performance of iCAR systems.

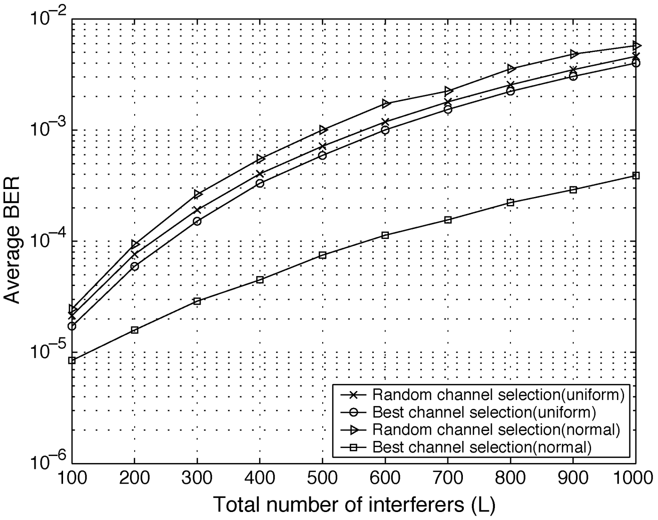


Fig. 9. Average BER versus the total number of interferers within the ARS coverage.

VII. CONCLUSION

In this paper, dynamic load balancing and sharing performance of integrated wireless networks is studied, via a representative system called iCAR system, which operates at the cellular and the ISM-band. It is shown that the realistic performance of iCAR systems will depend on the number of available ISM-band channels at a given point in time. The minimum number of relay channels required for dynamic load balancing and load sharing is also quantified. These results suggest that other users' interference in the unlicensed ISM-band could affect the dynamic load balancing and/or sharing capabilities of this wireless system. To see how this interference will affect the performance of iCAR, a simple illustrative example is provided. With this simple example, it is shown that the number of available ISM-band relay channels will indeed be limited due to other technologies' interference and, hence, the performance of iCAR will be strictly determined by the availability of relay channels. One solution to this problem may be to design iCAR systems with interference rejection or avoidance capability. To this end, in this paper, we also provide a simple interference avoidance solution employing a channel assignment scheme based on *C/I* measurements to improve the performance of iCAR. Results

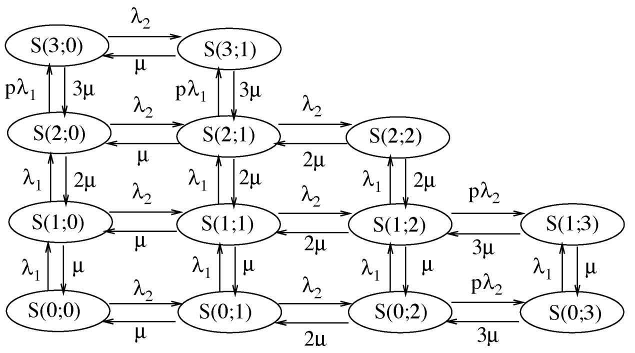


Fig. 10. State transition diagram for primary relaying for the two-cell system with $M = 2$ cellular-band channels and $K = 1$ ISM-band relay channels per cell.

show that the proposed simple solution can improve the performance by 12%–23% when the interferers are uniformly distributed and by 60%–90% when they have a normal distribution.

APPENDIX I

DERIVATION OF CALL BLOCKING PROBABILITY FOR PRIMARY RELAYING— EQUATION (1)

Since we assume Poisson arrivals and exponentially distributed channel holding times, we can describe the number of active users in the system via a Markov chain [25]. Hence, for the two-cell system under investigation, we can construct a 2-D Markov chain, states of which can be defined as $S(i_1; i_2)$, where i_1 and i_2 are the number of active users in cells 1 and 2, respectively. Fig. 10 shows the state transition diagram for primary relaying, when the number of cellular-band channels and ISM-band relay channels per cell is 2 and 1, respectively.

A closed-form expression for the state-probabilities can be found by solving the global-balance equations corresponding to this Markov chain

$$S(i_1;i_2)=\begin{cases}\frac{T_1^{i_1}T_2^{i_2}}{i_1!i_2!}S(0;0), & 0\le i_1\le M; 0\le i_2\le M\\ \frac{T_1^{i_1}T_2^{i_2}p^{i_1-M}}{i_1!i_2!}S(0;0), & M<i_1\le M+K;\\ & 0\le i_2\le 2M-i_1\\ \frac{T_1^{i_1}T_2^{i_2}p^{i_2-M}}{i_1!i_2!}S(0;0), & M<i_2\le M+K;\\ & 0\le i_1\le 2M-i_2\end{cases} \tag{13}$$

where $T_1 = \lambda_1/\mu$ and $T_2 = \lambda_2/\mu$ are the traffic intensities of cells 1 and 2, respectively. Using the fact that the sum of the state-probabilities is equal to 1, the idle-state probability $S(0;0)$ can be calculated and is given by (2). All other state probabilities can be obtained by substituting the value of $S(0;0)$ into (13).

Recalling the blocking events described in Section III-A, we can show that call blocking probability for primary relaying for cell 1 is given by

$$\begin{aligned}P_{B_P} = &\sum_{i_2=0}^{M-K} S(M+K;i_2) + \sum_{i_2=M+1}^{M+K} S(2M-i_2;i_2)\\ &+ \sum_{i_1=M}^{M+K-1} S(i_1;2M-i_1)\\ &+ \sum_{i_1=M}^{M+K-1}\sum_{i_2=0}^{2M-i_1-1} S(i_1;i_2)(1-p).\end{aligned} \tag{14}$$

Substituting the values of the state probabilities in (14), the call blocking probability in cell 1 can be calculated and is given by (1).

The procedure for deriving the call blocking probability, when secondary relaying is employed is similar. For this case, instead of a 2-D Markov chain a 4-D Markov chain is used, since we need to keep track of the location of the active users. The details of this analysis will not be given here, since it is beyond the scope of this paper. The interested reader is referred to [23].

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