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Improving handoff performance by utilizing ad hoc links in multi-hop cellular systems

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Abstract Handoff performance is a critical issue for mobile users in wireless cellular networks, such as GSM networks, 3G networks, and next generation networks (NGNs). When ad hoc mode is introduced to cellular networks, multi-hop handoffs become inevitable, which brings in new challenging issues to network designers, such as how to reduce the call dropping rate, how to simplify the multi-hop handoff processes, and how to take more advantage of ad hoc mode for better resource management, and most of these issues have not been well addressed as yet. In this paper, we will address some of the issues and propose a scheme, *Ad-hoc-Network–Embedded handoff Assisting Scheme (ANHOA)*, which utilizes the self-organizing feature of ad hoc networks to facilitate handoffs in cellular networks and provide an auxiliary way for mobile users to handoff across different cells. Moreover, we also propose a scheme enabling each BS to find the feasible minimum reservation for handoff calls based on the knowledge of adjacent cells' traffic information. Due to the use of multi-hop connections, our scheme can apparently alleviate the reservation requirement and lower the call blocking rate while retaining higher spectrum efficiency. We further provide a framework for information exchange among adjacent cells, which can dynamically balance the load among cells. Through this study, we demonstrate how we can utilize ad hoc mode in cellular systems to significantly improve the handoff performance.

Keywords Handoff management · Mobility management · Call blocking · Wireless cellular systems · Multi-hop cellular systems

1 Introduction

Traditional cellular networks are typical one-hop wireless networks since only the last hop transmissions are wireless between mobile terminals and base stations. The existing infrastructures of cellular systems make seamless connections for mobile clients possible via handoff management. In the last few years, due to the intensive development in wireless ad hoc networks and the multi-interfaced mobile devices such as smart phones, multi-hop cellular networks (MCNs), the integration of ad hoc mode into cellular systems, have started to emerge. The origin of this new type of networks comes from the intention that the new cellular networks should provide an all-IP platform, where new types of wireless networks, e.g., WiFi and WiMAX, and the traditional cellular networks can interwork seamlessly with variety of services. 3GPP has been already engaged in the study of this trend [1] and the specification of the interworking between WCDMA networks and WLANs was standardized [2]. It is now well-known that these

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wireless ad hoc networks, usually operated in the ad hoc mode, can be configured more flexibly with much lower cost and potentially higher data rate due to much shorter transmission range, though the coverage and mobility may not be guaranteed. Consequently, it is expected that MCNs can take advantages of both traditional cellular networks and wireless ad hoc networks.

An MCN is commonly considered as a cellular-based integration of a cellular network and ad hoc networks because ad hoc mode is treated as an additive component to cellular systems, which does not impair the traditional cellular infrastructure, which means that mobile users can access BSs through either direct (one-hop) connections or multi-hop connections. With the cellular-based MCNs under consideration, the first advantage over the traditional cellular systems we observe is the low cost of extending service coverage. Multi-hop wireless relaying can easily provide faraway wireless terminals with connections without building extra infrastructures (adding more BSs). Since the relay devices are usually much more portable than BSs, the flexibility in configuring more service connections is the second advantage we can expect. Moreover, this flexibility creates new ways, other than the traditional channel borrowing [3], to implement load balancing among different cells. Finally, with the ad hoc links bearing potentially higher data rate with extra spectrum, the system capacity can be expected to improve. Of course, we realize that the hidden assumption is that mobile terminals, in addition to the operator added ad hoc relaying stations, also participate in relaying and helping, which may not be practical if there is no incentive for the helping mobiles. Therefore, certain incentive protocols should be designed to stimulate mobile terminals to help the MCNs to operate. This topic will be investigated in a separate paper.

In this paper, we focus on the benefits that the ad hoc mode can bring to the handoff management. Handoff management is an important part of mobility management in Personal Communication Services (PCS) systems and any wireless cellular system in general in maintaining seamless connection [4]. Handoff dropping (HOD) rate is the major metric for assessing handoff performance and it usually requires the designed system to keep the HOD lower than certain threshold in order to meet the customers' satisfaction. In wireless cellular networks, HOD rate is usually guaranteed by bandwidth reservation for handoff calls in cells a mobile user most likely visits during its call connection. More bandwidth reservation can indeed meet the HOD rate requirement, but at the price of blocking more new call connections because less resource is made available for new call connections. Thus, a good handoff management should not only keep the HOD rate low, but also tie up less bandwidth. As a supplement to cellular systems, ad hoc links (links via relaying by using harvested either inband or outband resource opportunistically) create more opportunities for MNs to connect to BSs. Therefore, HOD rate is expected to decrease with ad hoc mode introduced into the cellular systems. Moreover, since handoff calls may be connected to adjacent BSs and thus use adjacent cells' reservation, each cell can reserve relatively less bandwidth to achieve the same HOD rate, and hence will accommodate more new calls.

As we alluded earlier, the introduced ad hoc links create plenty opportunities for access to the cellular systems. By choosing good link connections, we can decrease the call dropping rate while inappropriate choice of links may lead to poor performance. Careless design of handoff decision process may increase the handoff frequency, increase the call dropping rate, or lead to the inefficiency of resource usage. How to design the handoff strategy in the MCNs becomes a more complicated task than purely comparing the received signal strength (RSS) because of the options offered by the multi-hop connections. This problem for MCNs has not been touched upon previously. Most previous works assume that the relaying is made by specific planted devices (relay stations) according to proper network planning [5, 6]. This assumption really limits the utilization of benefits offered by the self-organizing ad hoc networking and diminish the flexibility of the ad hoc mode introduced. In this paper, we propose a new scheme, called *ANHOA (Ad-hoc-Network-Embedded Handoff Assisting Scheme)*, which utilizes the embedded, self-organized small-scale ad hoc networks to assist the handoffs. By exchanging information inside the embedded ad hoc networks, relay nodes can help handoff calls choose better handoff options and thus reduce the call dropping probability. Consequently, to meet a certain HOD rate, BSs can reserve less bandwidth for handoff calls than before. We also design an algorithm to enable adjacent BSs to lower the bandwidth reservation according to the traffic information of their cells to loosen up more bandwidth for new calls while meeting the HOD rate requirement. Furthermore, we have also proposed a framework for adjacent BSs to exchange information through which the load balancing among the surrounding cells can be implemented. Although there are some works on different issues in MCNs, such as cross-layer routing in [7], incentive schemes in [8], and the real-time traffic support in [9], they rarely address the handoff management and corresponding resource management by taking full advantage offered by the introduction of ad hoc mode.

The rest of the paper is organized as follows. Section 2 discusses the related works. In Sect. 3, we describe the system model and the basic ideas of this paper and in Sect. 4, we present the proposed ANHOA scheme. The algorithm for finding minimum reservation in MCNs and the framework of information exchange among adjacent BSs are given in Sect. 5. We carry out the performance evaluation in Sect. 6 and conclude the paper in the final section.

2 Related works

The integration of multi-hop ad hoc mode into cellular systems has been conceived in late 1990s and early 2000s. However, one of the first thoughts of integration is to introduce relaying systems into cellular systems. Hsu and Lin might be the first presenting the potential idea called Multi-hop Cellular Networks (MCNs) [10]. In this paper, the authors suggested to use multi-hop communications from mobiles to a base station via possibly multiple hops with lower transmission power so that more simultaneous communications can be accommodated. In iCAR (Integrated Cellular and Ad Hoc Relaying Systems), Wu et al. proposed to proactively deploy a new set of relaying nodes in areas where traffic congestion start forming and use these relaying nodes, called ad hoc relaying stations (ARSs), to relay the traffic from the congested cell to the non-congested cells where traffic can be served [5]. To investigate how much ad hoc relaying could enhance the system capacity in MCNs, Law et al. studied the capacity by assuming that a cell is divided into two co-centered areas where direct communications are carried out within the near range between mobiles and the BS while multi-hop communications will be carried out only when mobiles are outside the near range [11] and found that for certain scenarios, the system capacity can indeed be increased.

To take more advantages of relaying capability and by harvesting potential outband resource, Luo et al. proposed a unified cellular and ad-hoc network architecture (UCAN) based on 1xEV-DO (HDR) and 802.11b [8]. This work was motivated by the observation that a higher downlink data rate may be needed for many applications. By allowing wireless clients to relay the downlink traffic in this scheme, the system can achieve better throughput performance. The authors developed the discovery algorithm of wireless proxy (relay clients), which plays very important role in implementing their proposed architecture. In view of the potential gain in using ad hoc mode, future generation wireless cellular standards have also considered this issue and proposed ODMA (Opportunity Driven Multiple Access) protocol [12], which is a similar scheme to UCAN [8], but focuses on the improvement of data rate by allowing relaying.

There are many proposals on ad-hoc/cellular integration architecture in the literature which address different aspects of various integrated networks. Cavalcanti et al. provided a survey of all these integrated networks [13]. Some of the features of the related works are compared. Le and Hossain have also given a survey on the existing MCNs [14], which focuses more on resource management. Cho et al. dealt with handoff issues of various types in MCNs [6]. In [15], Bhargava et al. took a different approach and intended to use cellular networks to help the management of ad hoc networks by utilizing the benefit of coverage offered by cellular systems. As we can observe, most integration research works are based on cellular systems, focusing more on enhancing the performance of cellular systems because cellular systems are deeply commercialized and they can provide seamless coverage and mobility service.

3 System model and basic idea

3.1 System model

In the MCNs, there are two operational modes for a link. One is the traditional cellular operational mode using the cellular spectrum and following the cellular standard. The other we call the ad hoc mode may use outband spectrum and follows the ad hoc protocols such as IEEE802.11. The service coverage areas are divided into cells as in traditional cellular system while ad hoc links can cross the boundaries of adjacent cells when relaying traffic. Each BS is assumed to have the same transmission power as before which can cover the whole cell area.

Since the focus of this paper is the handoff issue in MCNs, in our model here, each MN (mobile node or mobile terminals or user equipment) is always bound to one certain BS, no matter whether via only cellular links or via multi-hop connections. We call the handoffs involving multi-hop connections as the multi-hop handoffs. When an MN moves from one cell to another and chooses the target BS as its serving BS, the handoff process is no different from that in the traditional cellular systems. Only when a multi-hop connection exists either before or after an MN alters its connection, do the handoffs face the new type of network challenges. Figure 1 illustrates the multi-hop handoffs in a multi-hop cellular system.

In Fig. 1, MN A moves from cell 1 to cell 0. Unfortunately, the BS in cell 0 has no spare spectrum. In the illustrated scenario, MN A has two options. It can either access the BS 5 through MN B or access BS 7 through MN C and MN D. Either option can enable MN A to access to the cellular system.

Usually, a connection with more hops implies more potential disconnection vulnerability due to the mobility of intermediate nodes. There are also cases that the multi-hop connection may have high data rate due to less interference and shorter distance between nodes on the connection. How to choose between a single-hop connection and multi-hop connection is a challenging but important question. In this paper, to simplify the analysis, we assume that each MS

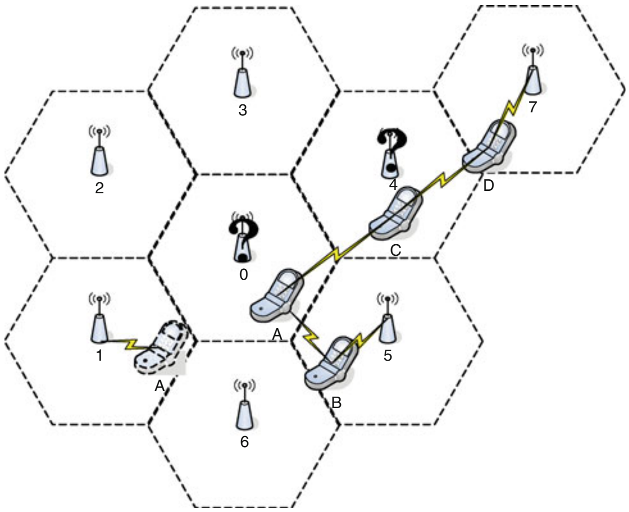

Fig. 1 Model of multi-hop handoffs

attempts the direct connection first before sinking multi-hop connection unless being redirected. When a direct connection is not available, a disconnected MN, or an MN looking for a handoff, searches for the nearby ad hoc spectrum to find the alternative connections. Some connected MNs broadcast their corresponding BSs' IDs and some other information via the ad hoc spectrum. For new calls, MNs search for all possible connections until they succeed. For handoff calls, due to the time limit of signaling process, MNs make several attempts to connect to different BSs until they succeed or the time limit is reached. The BSs' IDs are used to prevent repeated attempts. The connected MNs are responsible for relaying the connecting MNs' requests to the destination BS. The destination BS allocates cellular spectrum resource to the connecting MN in care of the last hop relay MNs. The BS keeps the information of the relay relationship of its serving MNs in order to deliver packets correctly. As a remark, the security may be a concern because the MNs on the connection may cause security leak. We will address the security issue elsewhere.

In traditional analysis of cellular networks, it is assumed that the call droppings caused by link failure are usually ignored and only the call dropping is caused mainly by handoff failure. In fact, a connection can be disconnected due to wireless link failure, especially when the connection is multi-hop. Thus call droppings caused by the failure of ad hoc links cannot be ignored in MCNs for our analysis. The call dropping rate can be expressed in such a formula as follows.

$$P(dropping) = 1 - (1 - P(con\_fail)) \times (1 - P(HOD)) \tag{1}$$

$P(HOD)$ is the probability of call dropping due to handoff failures. $P(con\_fail)$ is the probability of call dropping caused by connection failures. Multi-hop connections is disconnected more easily due to the smaller transmission range, mobility of relay nodes and nature of multiple-hop. Obviously, the call dropping rate is related to the hop counts of the multi-hop connection and the mobility of relay nodes as well as the roaming nodes.

To maintain a certain $P(HOD)$ level, certain bandwidth should be reserved for handoff calls. If there is only one cell's resource under consideration, according to Markov Chain model, such as [16], the HOD probability can be obtained when the traffic arrival and departure rate are given by

$$P_0 = f(\lambda_n, \lambda_{ho}, \mu, Rsv) \tag{2}$$

where *f*() is the derivation function of HOD rate which is described in detail in "Appendix". We denote the HOD rate as P_0 when only one cell's resource is considered. The arrival rates of new calls and handoff calls are denoted as λ_n and λ_{ho}, respectively. The departure rate of all calls is denoted as μ and Rsv is the number of reservation channels.

We know that the transmission range of an MN is much smaller than that of a BS and many MNs are highly mobile. It seems ad hoc mode could not significantly help the cellular system due to much shorter span of certain links. However, there are still many relatively stationary MNs existing in the system because low mobility can achieve higher data rate or purely because of users' behaviors. Devices such as ARS in [5] can also be introduced to increase the stability of multi-hop connections. Therefore, due to the existence of plenty of potential relay nodes, we can rely on multi-hop connections to improve the performance of cellular systems.

3.2 Basic idea

In MCNs, beside the BSs, the existing relay nodes can also assist the roaming MNs to complete handoff process via multi-hop connections. The multiple handoff options may connect the same roaming MN to different BSs, or to the same BS via different paths. Among multiple handoff options, how to find the best is very important but challenging. Connecting to inappropriate BSs through inappropriate relay nodes at inappropriate timing may not only increase the handoff frequency, increase the call dropping rate, but also lead to the inefficiency of resource. In order to make the right decision, it is important for roaming nodes to collect more information about the candidate choices. It is well known that self-organization is one of the major advantages of ad hoc networks, and thus relay nodes can easily exchange information in ad hoc mode. When the relay nodes form small-scale ad hoc networks, the resource information can be exchanged and maintained periodically within the networks, just as in some routing algorithms in IP networks. The roaming nodes can obtain the necessary information to enable the path selection for a connection with better QoS and lower the call dropping probability. Large-scale ad hoc networks are not suitable for this task because the information exchange will create too much signalling overhead.

The traditional way to control the HOD rate in cellular networks is to adjust the bandwidth reservation for the handoff calls [17]. Higher reservation means lower HOD rate. However, blindly increasing the bandwidth reservation also lead to the higher call blocking rate for new calls, thus decrease the spectrum efficiency. Therefore, searching for the optimal reservation which can also satisfy the constraint of the HOD rate should be the goal for each BS. For MCNs, due to the existence of multi-hop handoffs and multiple handoff attempts, each BS can practically have a smaller bandwidth reservation. The knowledge of adjacent cells' traffic can help each BS making resource management more efficient, furthermore, balance the load among different BSs.

Based on the insights above, in this paper we propose two schemes to improve the handoff performance. In the first scheme, we let a part of the stationary MNs form small-scale ad hoc networks to exchange and maintain necessary information for the potential handoffs. When handoffs occur, the roaming MNs can utilize the present information to choose the best choice for handoffs. The utilization of self-organizing characteristic of ad hoc networks in MCNs is manifested through the use of multi-hop handoffs. The second scheme deals with the bandwidth reservation at each BS. Each BS gathers the traffic information of its adjacent cells, takes the prospective multiple handoff attempts for roaming MNs into account and makes the least reservation. This mechanism is then further developed to a framework which can balance the load among different cells when traffic load is significantly unbalanced.

4 ANHOA: ad-hoc-network-embedded handoff assisting scheme

4.1 Overview

Multi-hop connections can reduce the HOD greatly in that more opportunities are provided than before. However, although potential paths exist in these nodes, it may not be easy to find the best choice. In MCNs, there are probably many connected MNs surrounding one disconnected MN. Among all these potentially connected nodes, some may have already been connected to the BSs that have no spare channels to accommodate new connections while others are highly mobile and not suitable for relaying. Although several attempts for a handoff process are generally acceptable, trial and error approach is not a good idea. Fortunately, as we all know, information can be effectively gathered and shared using the power of networking. To make information exchange more effective and more helpful to the handoffs, we may prefer to select stationary nodes to form mobile ad hoc networks (MANETs) to assist handoffs. Obviously, when the scale of these assisting networks becomes large, the coverage can be wider and the handoff can gather more help. On the other hand, the maintenance of the assisting networks will become more difficult and the information exchange will be less effective. Thus, we need to employ stationary, small-scale ad hoc networks to more effectively assist the multi-hop handoffs in cellular systems. Based on this argument, we propose our scheme handling multi-hop handoffs, called "Ad-hoc-Network-Embedded Handoff Assisting Scheme (ANHOA)", in which we address how to select nodes for the relaying and how to form the handoff assisting networks. In this paper, we focus on the handoff issues and simply assume that these networks can be formed by the instruction of operators.

4.2 Architecture and roles

We first describe the network architecture and roles of the assisting networks in Fig. 2. In this network architecture, each of these embedded ad hoc networks covers the area which may cover several adjacent cells. As Fig. 2 shows, several MNs form one embedded ad hoc network (EAN) in the cellular systems which spans across several cells. In Fig. 2, the circled nodes are the backbone nodes and the

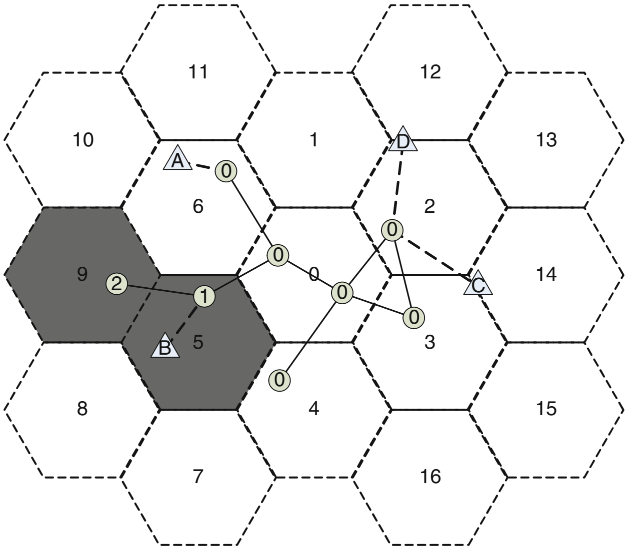

Fig. 2 Embedded ad hoc network in cellular system

solid lines between them stand for the relatively stationary links. The triangular nodes stand for the roaming nodes which are searching for BS connections with the help of the embedded ad hoc networks. We call these nodes "attaching nodes (ANs)". The nodes in the backbone connecting directly to the BSs are marked with "0" inside the circles. We call these nodes "portal nodes (PNs)" because they have portal capability of connecting to the backbone cellular system. Other nodes in the backbone not directly connected to BSs use the number inside the circles to stand for the hop counts to portal nodes. We call them "relay nodes (RNs)". RNs and PNs form the backbone of the embedded ad hoc networks which assist multi-hop handoffs in the cellular system. The ANs which cannot have the direct connection to BSs use the EANs to find alternative connections. The backbone node which have direct connection to the attaching nodes are their "dock nodes (DNs)". ANs' DNs do not have to be PNs. Each PN should also know the corresponding ANs which connect to a BS through it via different DNs. These ANs are called the "subordinate nodes (SNs)" of this PN.

4.3 Information maintenance of EAN

The construction of EANs and the routing maintenance are omitted in this paper. We assume that the EANs have been already constructed, and the routing paths to potentail PNs, the link capacity status and the interference link set of each link are all known, which can be used to estimate the so-called "portal capacity (PC)" and enable each AN to make the handoff decision. Notice that each backbone node in EANs should maintain a table storing the link capacities of all its neighboring links and to be updated when some interfered paths are taken or released.

Each node in the backbone of EANs is a potential DN for roaming MNs. When a roaming MN attaches to an EAN and searches for a multi-hop connection to a BS, its DN in the EAN provides connection information for it and then the handoff attempts follow. Portal capacity in this paper is defined as the maximum achievable bandwidth along the path in the EAN from DNs to the connected BSs.

For each PN, its own portal capacity is the average available bandwidth obtained from the Markov chain model. Given the arrival rate λ and departure rate μ of a cell, according to Markov chain model as [16, 17], the expected unused channel/bandwidth can be derived. For each relay node, the portal capacity to different PNs also depends on the path capacity of different paths. Since all links of one path share the same medium, they may tend to interfere with each other, hence the path capacity is not simply the minimum of link capacities on the path. It needs to take the link contention/scheduling of the channel into account. According to the result of [18], the path capacity is at most 1/4 of minimum link capacity. Therefore, we use the following equation to estimate the portal capacity.

$$PC = min(EstCellBW, \frac{1}{min(4, HC)} min_{i \in \mathbb{L}}(L_i)) \qquad (3)$$

where *EstCellBW* denotes the estimated available bandwidth in cellular spectrum, *HC* is the hop count from DN to PN, L_i denotes the link capacity of link i and $\mathbb{L}$ denotes the link set of the corresponding path.

This information is used by each AN to determine which PN to connect. The information about the connection to different BSs via different PNs is maintained in every backbone node of the EAN. Besides the link capacity status table aforementioned, each backbone node in EANs should maintain two tables which store the information of available connection resource and the information of its ANs, respectively.

The portal capacity entries in the table are used by ANs to choose PNs with better dropping probability. These entries are correlated with each other. In other words, if one PN is chosen by some AN, the portal capacity of other paths as well as this path will probably also change. The reason is that different paths may share same portal node, or share same certain link, or, links from different paths interfere with each other with high probability.

For each PN, it is necessary to collect and update the information of its SNs. Therefore, the following table is required to be maintained in every PN besides the above two tables.

When the link capacity of each link changes, the portal capacity of each path is required to adapt accordingly in order to reflect the BS connection capability in real time. The change of the arrival rate λ or the departure rate μ causes the change of *EstCellBW*, and thus the change of *PC*. These changes should be broadcasted in the EAN and each backbone node should update its entries accordingly. When one AN acquires a certain amount of bandwidth from one PN, all the intermediate links subtract the same amount of bandwidth from each link capacity. Moreover, all the interfered links in the EAN should also subtract the summation of the occupied bandwidth they sense. The above information related to links is not stored in the above 3 tables, but in the link table we assumed before. *PC* in Table 1 and *OPC* in Tables 2 and 3 are calculated based on the link capacity information via Formula 3.

In addition to these *PC* related updates, when an MN enters or leaves the EAN, the corresponding relationship should also be updated. These updates will be referred to as the "relationship update" in the following section. Upon the arrival (bandwidth granting) or departure (bandwidth releasing) of one SN, a PN notifies all the intermediate backbone nodes about this event hop by hop till the DN. The PN adds/clears the corresponding SN entry. The PN

Table 1 Portal nodes' information table

PNID	The ID for the candidate of portal nodes
BSID	The ID of the BS which connects to the corresponding portal node
EstCellBW	Estimated available bandwidth of corresponding BS
HC	Hop counts to the corresponding portal node
PC	The available portal capacity to the corresponding BS

Table 2 Attaching nodes' information table

ANID	The ID of the attaching node
PNID	The ID of the attaching node's corresponding portal node
HC	Hop counts to the corresponding attaching node
OPC	The occupied portal capacity by the corresponding attaching node

Table 3 Subordinate nodes' information table

SNID	The ID of the subordinate node
DNID	The ID of the subordinate node's corresponding dock node
HC	Hop counts to the corresponding docking node
OPC	The occupied portal capacity by the corresponding subordinate node

and all other corresponding backbone nodes update the *PC* information, and the DN adds/clears the corresponding AN entry. Besides the update of these 3 tables, the change of *PC* should trigger the change of link status table of the corresponding link, and thus the link status table of interfered links.

4.4 Handoffs via ANHOA

Apparently, introducing the ad hoc mode gives handoff decision more flexibility in cellular systems. The first possible change of handoff procedures is that with the existence of EANs, handoffs might involve multiple nodes in the EANs. Previously, the handoffs are always from one cell to another, with direct connections to BSs. With the existence of EANs, handoffs can also possibly take place from one EAN to another, from one EAN to a direct connection or vice versa, or within the same EAN. Procedures for these types of handoffs should be specified to avoid the possible resource waste and service interruption.

Moreover, the timing for a handoff also becomes complicated. In the traditional cellular systems, the timing of handoffs is when the current BS's signal strength is below a certain threshold and the alternative BS's signal strength is above a certain threshold (or more complicated strategy). When multi-hop connections are allowed in cellular systems, handoff decision are given more options and can be more flexible than before.

When an MN travels in the MCNs, it uses its ad hoc mode radio searching for the existing EAN signals while using its cellular radio for cellular services. It measures the signal strength of the detected signals (including direct BSs signals and EAN signals) and maintain its set of potential handoff candidates. Handoffs without EAN involved are no more different from the traditional cellular handoffs. Multi-hop handoffs happen when certain conditions are met. When multi-hop handoffs are needed and there is an embedded ad hoc network accessible, ANHOA can be executed.

The basic procedure of EAN-supported handoffs has several elements just as the traditional handoffs as shown in Fig. 3. Update requests are sent to the new BSs. New BSs need to retrieve users' information from the old BSs. The connections are then established between the new BSs and MNs. Finally the old BSs are required to clear the old record. Small difference from the traditional cellular handoff procedures is the extra information that the update request should carry, the Portal Node ID. This information is used for the release of the old multi-hop connection through the same EAN or another one.

Although the extra signallings within EANs bring extra cost to the handoff procedures, it can be seen as the price to pay for alternative handoff options, which is intuitively better than the traditional handoffs only. The signallings within EANs simply deal with the updates of 4 aforementioned tables. These updates change the nodes' relationship corresponding to the multi-hop connections. If a handoff happens within a single EAN, the procedure can be simplified because the only thing needs to do is the "relationship update" as mentioned before.

ANHOA is proposed to provide mechanisms to support multi-hop handoffs in cellular systems with the aid of EAN. Although there are a lot of issues in handoff timing and handoff procedures, we focus on how the MNs choose handoff options so that the call dropping can be greatly reduced.

First, let us describe the handoff procedures via ANHOA. Within the transmission range of any EAN node, the AN can acquire the knowledge of all PNs in the EAN and the *EstCellBW* of each connected BS. The AN uses the "handoff decision algorithm" to choose a suitable PN and requests the DN to forward the update to the chosen PN. If the new EAN is different from the old EAN, which can be learned from the EAN ID information in the update request message, the "relationship update" of the old EAN is separated from the one of the new EAN, even if they connect to the same BS. The DN forwards the update request to the PN, with the requested QoS information and the old BS and old PN (null-valued if there is no). After QoS negotiation, the PN sends the update request to the new BS with the negotiated QoS. Before granting the update request, the new BS

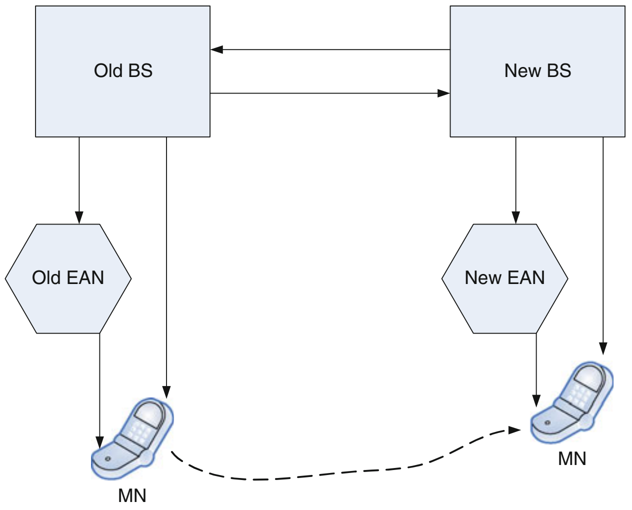

Fig. 3 EAN-involved handoffs

needs to request the subscriber information from the old BS and allocate corresponding resource to the AN, in care of the PN. Especially, if BS does not change, the handoff only requires BS to update the MN's PN information. On the other hand, when EAN does not change, the adding and removing of the "relation update" can be processed within the same EAN. When the BS does not change and the PN changes, the connected BS only needs to update the MN's PN information. When neither BS nor PN changes, BS does not need to do anything and all the handoff procedure is carried out by the EAN. Therefore, ANHOA can relieve a lot of signaling pressure off BSs by taking care of a lot of handoffs within EANs.

Beside the signaling, for the packets to be forwarded from the ANs to the PNs or the opposite direction, it is both feasible to use routing and tunneling approach. Considering we assume EANs to be small-scale ad hoc networks, routing is more efficient because tunneling may cause more delay due to encapsulation and decapsulation.

Notice that when a multi-hop handoff happens within an EAN, the procedure can be very simple and convenient. The clients can get the seamless service at very low price. For the continuity of the service, within one EAN, the MN can choose the same PN as before. In this way, the handoff procedure only involves the path information update in the corresponding nodes in the EAN.

ANHOA can also help new calls. This mechanism does not discriminate new calls from handoff calls although we should let handoff calls have higher priority as done in the traditional cellular systems.

4.5 Handoff decision algorithm

In this section, we present the handoff decision algorithm used by MNs in the environment along with EANs. The input of the algorithm is the candidates of handoff destinations, either BSs or EAN nodes, and their corresponding information. The output is the choice of the handoff destination. The criterion is to have lower call dropping and more QoS satisfaction. In this paper, we assume QoS can be always satisfied when a connection is available and we ignore the QoS satisfaction. As we formulate in Eq. (1), call dropping can be caused by handoff failure or by physical layer communication failure. For each connection candidate, i.e., one DN's connection to one PN, the corresponding call dropping rate is calculated. The AN compares the call dropping rates of all candidates and find the one with the lowest call dropping rate. Note that one DN can have more than one candidate because it can connect to different PNs.

There are several factors that affect the handoff performance. The first is the expected bandwidth of the destination BS. With the knowledge of arrival rate and departure rate of the corresponding BS, the steady probability of each state can be derived and thus the expected available bandwidth can be derived as well.

$$P_i(BS\_HOD) = f(\overrightarrow{\lambda}_i, \overrightarrow{\mu}_i, Rsv) \tag{4}$$

$$EstCellBW_i = g(\overrightarrow{\lambda}_i, \overrightarrow{\mu}_i, Rsv) \tag{5}$$

where $P_i(BS\_HOD)$ is the HOD rate derived based on the knowledge of reservation Rsv, the initial/handoff call arrival rate $\overrightarrow{\lambda}_i$ and departure rate $\overrightarrow{\mu}_i$ of BS i, $f()$ and $g()$ denote functions of $P(BS\_HOD)$ and $EstCellBW$, respectively.

The second factor is the handoff cost in terms of signaling traffic. If a handoff takes place within the same EAN without changing BS, the handoff cost is in fact very small. It is more appealing than those handoffs that changes BS, PN, or even EAN. We denote the HOD probability when only BS changes, only PN changes, and only DN changes as $P(BS\_HOD)$, $P(PN\_HOD)$, and $P(DN\_HOD)$, respectively. With $P(PN\_HOD)$ and $P(DN\_HOD)$ of each candidate obtained from measurements, the one-time multi-hop HOD rate of each candidate can be derived via the following formula.

$$\begin{aligned} P_k(one\_HOD) = 1 - (1 - P_k(BS\_HOD)) \\ \cdot (1 - P_k(PN\_HOD)) \cdot (1 - P_k(DN\_HOD)) \end{aligned} \tag{6}$$

If the BS or the PN does not change, the corresponding HOD rate takes 0 value.

The third factor is the hop-count of the multi-hop connection. If the multi-hop connection has higher hop-count, it will be more vulnerable to disconnect. In this paper, we assume all EAN nodes have similar mobility, thus we can derive the connection failure probability via the following formula.

$$P_k(con\_fail) = 1 - (1 - P_k(one\_hop\_fail))^{hop\_counts_k} \quad (7)$$

The last factor is the relative position of destination BS to the MN's movement. If the BS locates along the direction of the MN's movement, the MN can avoid some unnecessary handoffs in the future, thus the call dropping probability can be further reduced. Given that the MN keeps the moving history, it can have the conditional probability for each candidate of the handoff destination $P(BS_i|BS_h)$, where BS_i stands for the BS i and BS_h stands for the previously-visited BSs. The extra HOD probability can be expressed via the following equation.

$$P_i(extr\_HOD) = (1 - P(BS_i|BS_h)) \cdot \overline{P(HOD)} \quad (8)$$

where $\overline{P(HOD)}$ denotes the averaged HOD rate derived by averaging the overall chosen dropping rates of the MN's recent handoffs. Therefore, the overall HOD rate for each candidate can be derived as below. The overall call dropping rate can be derived via formula (1).

$$P_k(HOD) = 1 - (1 - P_k(extr\_HOD) \cdot (1 - P_k(one\_HOD))) \quad (9)$$

After we calculate the $P_k(call\_dropping)$ for each candidate k, we simply choose the handoff option (the combination of BS and PN) with the smallest call dropping rate. Although there exist other factors that can affect the handoff performance, like QoS satisfaction, we will not present the details here because we think we can easily extend our framework to accommodate more factors. There do exist signaling overhead due to the information exchange among EAN nodes. However, this signaling overhead exists only in the ad hoc spectrum which only affects the ANHOA system itself. How to balance this signaling overhead and the assisting performance within ANHOA system will be our future work.

5 Resource management for multi-hop handoff

Multi-hop connection demands good resource management along the connection and in adjacent cells, which is addressed as follows.

5.1 Minimum reservation

To maintain a certain level of HOD rate, each BS should reserve certain amount of bandwidth for handoff calls. If the reservation is not enough, the expected HOD rate will be exceeded. However, since the reserved resource is separated from the shared resource, if the reservation is unnecessarily high, the blocking rate for new calls will increase, leading to dissatisfaction in new call blocking. Therefore, the focus of resource management is to find the minimum resource reservation which meets the HOD requirement. In MCNs, since we can make more than one attempt for handoff, we can expect lower HOD rate than in one-hop cellular networks with the same traffic load and same reservation even though multi-hop connections bring in extra traffic from the adjacent cells. From the MNs' point of view, one rejected handoff request in one cell in traditional cellular systems has always a certain probability to access the other cells through ad hoc links. From the BSs' point of view, we can reserve smaller amount of bandwidth to meet the same HOD rate requirement for the same traffic load but with multi-hop handoff connections so that we can gain larger amount of shared bandwidth resource to achieve higher trunking efficiency.

In MCNs, a given HOD rate is the input of a reservation scheme design. This input specifies the expected HOD rate for each MN when it is physically within a certain cell. We denote the required HOD rate for each MN in certain cell as $P_r(HOD)$. Our goal is to find the minimum feasible reservation Rsv. In other words, we need to find the relationship between $P_r(HOD)$ and P_0 in Eq. (2). Different from what is described in the ANHOA scheme, $P_r(HOD)$ cannot be derived from certain candidates' information because it is an expected value for the whole cell. We assume each handoff MN first attempts to access its current cell and then try the neighboring cells one by one with a certain time limit. Therefore, besides P_0, the HOD rates of the adjacent cells are also needed in finding $P_r(HOD)$.

In the proposed algorithm of finding the minimum reservation, each BS is required to collect the HOD rate information of the adjacent cells. To simplify the analysis, we assume that each BS only considers the multi-hop handoffs to its one-hop neighbors. The periodic message exchange among the neighboring BSs can provide a mechanism to acquire this information. BSs use the past arrival rate λ, departure rate μ, and the reservation Rsv of the neighboring cells as the predictive value of next time interval. According to the previously measured value λ, μ and the current reservation Rsv, each BS calculates its own one-attempt HOD rate and broadcast this value. Note that the measured arrival traffic λ_{ho} consists of the original handoff traffic and the handoff traffic rejected in adjacent cells. The broadcasted value of one-attempt HOD rate $\tilde{P}_i$ is taken as the input of calculating the minimum reservation. Besides the HOD rate of neighboring cells, each BS also needs to know the probability that multi-hop handoffs can access the adjacent cell. This access probability, corresponding to a surrounding BS i, denoted as q_i, can be measured by dividing the number of calls in current cell (BS 0) which have access to BS i to the total number of calls in the current cell. Obviously, this measurement requires the handoff calls to report extra information to BS, the accessibility to other BSs.

$$
\begin{aligned}
P_r(HOD) =& P_0 \cdot \Bigg(\prod_{i=1}^{M} (1 - q_i) \\
&+ \sum_{i=1}^{M} \frac{\tilde{P}_i}{M} \cdot q_i \prod_{l}^{M} (1 - q_l) \\
&+ \sum_{i=1}^{M} \sum_{j \neq i}^{M} \frac{\tilde{P}_i \cdot \tilde{P}_j}{2! \cdot C_M^2} \cdot q_i \cdot q_j \prod_{l \neq i,j}^{M} (1 - q_l) \\
&+ \cdots \\
&+ \sum_{i_1=1}^{M} \cdots \sum_{i_N \neq i_1,\ldots,i_{N-1}}^{M} \frac{1}{N! \cdot C_M^N} \prod_{k=1}^{N} \tilde{P}_{i_k} \\
&\cdot q_{i_k} \prod_{l \neq i_1,\ldots,i_N}^{M} (1 - q_l) \Bigg) \qquad (10)
\end{aligned}
$$

With these broadcasted $\tilde{P}_i$ and measured q_i, we can find the expression of the final HOD rate as in Eq. (10). While we take the required HOD rate as $P_r(HOD)$, we can derive the minimum reservation by incorporate formula (2). We use N to denote the maximum number of attempts after the direct handoff attempt fails and M to denote the number of neighbors of the current cell.

Note that in Eq. (10), the required HOD rate is simply the summation of the probabilities that after a handoff fails in the current cell, it fails in different numbers of other cells.

In actual MCNs with ANHOA scheme, roaming MNs attempt to connect to the proper BSs in a more intelligent way rather than connecting to the adjacent cells by using trial and error approach. Therefore, the overall HOD rate can be reduced further. Moreover, a rejected direct handoff call can attempt to connect to not only the adjacent BSs but also BSs further away, as long as the multi-hop paths exist. Eq. (10) considers only the adjacent BSs in order to simplify the derivation of the minimum reservation.

Let us revisit Eq. (10). When each q_i has value 1, which means MNs in the current cell can access the resource of all the adjacent cells, this system can be seen as a larger cell consisting of all adjacent cells with aggregated resource from all adjacent cells. Obviously, this system has higher trunking efficiency, which can lower the call dropping rate and the requirement for resource reservation. When more than one hop neighboring cells are considered, even higher trunking efficiency and lower call dropping rate can be expected.

5.2 Load sharing among adjacent cells

With the hanodff options via multi-hop connections an MN can achieve a much lower overall HOD rate $P_r(HOD)$ than the HOD rate derived from the arrival/departure rate and reservation, P_0, based on the one-hop connection. However, we should not only focus on the requirement of $P_r(HOD)$, but also need to maintain a certain resource to control P_0. High P_0 implies too much rejected traffic from current cell, which will overflow to other cells with $P_0 \cdot \lambda_{ho}$, even though $P_r(HOD)$ can still be satisfied. This part of traffic, called "*permeated traffic*" in this paper, will deteriorate other cells' HOD rates, as a chain effect, due to repeated handoff attempts. This means if one BS keeps a significantly insufficient bandwidth reservation and mostly relies on other cells' help, it can end up deteriorating surrounding cells' HOD performance. The mathematical explanation for this situation is that the derivations of $P_r(HOD)$ and P_0 are based on the assumption for an ergodic system. If the reservation cannot support the arriving handoff calls, this system is not ergodic anymore. Consequently, Eq. (10) is not valid any more. When one of the cells in the neighborhood has been overloaded with traffic, this problem might be inevitable and even more protuberant. Therefore, a certain threshold should be set to ensure that none of the cell is overloaded. Furthermore, load balancing mechanism is necessary in MCNs to utilize the whole resource more efficiently. When one cell is heavily loaded, load balancing mechanism can utilize the adjacent cells' reservation to maintain the required HOD rate.

In this paper, we build a framework for this purpose. In this framework, the traffic information in adjacent cells is exchanged and shared and the minimum reservation is calculated in a distributed fashion. More importantly, when some cell is heavily loaded, this framework provides a mechanism for BSs from other cells to take over part of the traffic so that each cell can maintain a relatively low HOD rate, $\tilde{P}_i$. This framework is called "Traffic Information Exchange for BSs' Reservation Calculation Procedure". The reservation calculation is done periodically by each BS. Between two consecutive periods of calculation, there are three phases: information collection, load balancing, and reservation calculation/information broadcasting.

In the first phase, each BS collects its neighbors' traffic load in the previous period, the neighbors' $\tilde{P}_i$, and the corresponding access probability q_i. Each BS can predict the traffic load according to the previously measured traffic, which consists of local traffic and permeated traffic from adjacent cells. The traffic load is measured in Erlang, i.e., traffic intensity. If the traffic load does not exceed a predefined threshold, λ_{th}, the second phase can be skipped. Otherwise, the overloaded BS requires its neighbors to take over part of its traffic load. The requests to different neighboring BSs will be based on the access probability, q_i. When requests have been granted, indication will be broadcasted in the broadcast channel (BCCH) to redirect part of the traffic to other cells. The redirection operation for partial traffic can be implemented by a simple modulus operation by each MN. Thus the accurate traffic load of each BS is known, which can be expressed as follows.

$$\lambda_n(i) = \lambda_{nLocal}(i) + \lambda_{nTkov}(i) + \lambda_{nPerm}(i)$$
$$\lambda_{ho}(i) = \lambda_{hoLocal}(i) + \lambda_{hoTkov}(i) + \lambda_{hoPerm}(i)$$

The equations mean that the traffic load of handoff calls (with subscript *ho*) or new calls (with subscript *n*) consists of the local traffic (λ_{Local}), permeated traffic from neighboring cells (λ_{Perm}) and the overflow traffic from neighboring cells (λ_{Tkov}).

During reservation calculation phase, each BS calculates its own P_0 beforehand, according to the latest traffic load and the reservation. If any BS is requested for taking over partial traffic from current BS, the calculation of corresponding P_0 should include this partial traffic. With $\tilde{P}_i$ and q_i known, the minimum reservation can be calculated via Eq. (10) and Eq. (2).

The signaling overhead caused by the periodical information exchange will not affect the system performance substantially because of two reasons. First, the signaling is through wired-line which is not seen as the bottleneck of the system. Second, the signaling is among adjacent BSs and is periodical so that the overhead is controllable.

6 Performance evaluation

In this section, we study the benefits that multi-hop connections can bring to the cellular systems in terms of handoff performance.

Firstly, we look into the HOD rate when the reservation of each BS remains unchanged. We study a cellular system with seven-cell frequency reuse. For a single cell, we calculate the HOD rate according to Eq. (2). The detailed derivation is briefly introduced in the "Appendix", based on the model in [16]. The basic setting of resource parameters is listed in Table 4.

Each BS calculates the overall HOD rate according to Eq. (10) with the knowledge of its adjacent BSs' single-cell HOD rates. The access probability to the neighboring cells are set as the same value. This calculation gives the statistical HOD rate in a cell. The choices of multi-hop handoffs are assumed to be chosen randomly. With ANHOA scheme, MNs are expected to achieve better performance because more handoff opportunity and the intelligent handoff decision algorithm should mitigate the ongoing connection call drop.

Table 4 Simulation setting for each cell

Number of channels	30
Number of reserved channels	5
Average number of initial calls	40
Average number of handoff calls	120–270
Access probability	0–1
Average call intensity per user	0.1erl

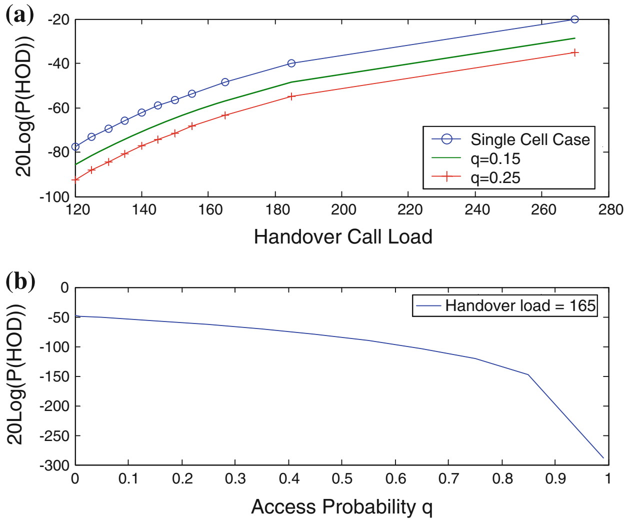

Fig. 4 HOD rate

In Fig. 4, the overall HOD rate of the center cell has been shown. Part (a) shows the relationship between traffic load and HOD rate. From Part (a), we can see that when traffic load increases, the HOD rate increases accordingly. With the help of adjacent cells, HOD rate can be reduced greatly. From Part (a), we can see that even with a small access probability, such as $q = 0.25$, the HOD rate can be improved with 20dB. We can also see from Part (a), when traffic load increases to a certain level, the HOD rate will deteriorate badly. The reason is that the current reservation cannot support the traffic load and the rejected traffic also forms a big burden on the adjacent cells. Part (b) shows the relationship between HOD rate and different access probabilities under a certain traffic load. We observe that when access probability increases, the HOD rate decreases dramatically.

Secondly, we evaluate how the channel reservation is relieved with the help of adjacent cells. Lower reservation can also greatly reduce the call blocking rate of new calls. In this part of simulation, we set the required HOD rate to 0.5×10^{-3}. Under this constraint, each BS finds the minimum channel reservation. In Part (a) of Fig. 5, the numbers of reserved channels are shown with different traffic loads. We can see that without the help of adjacent cells ("Single Cell Case" in the graph), more channels need to be reserved to achieve the required HOD rate. When traffic load becomes larger, reservation does not work for the

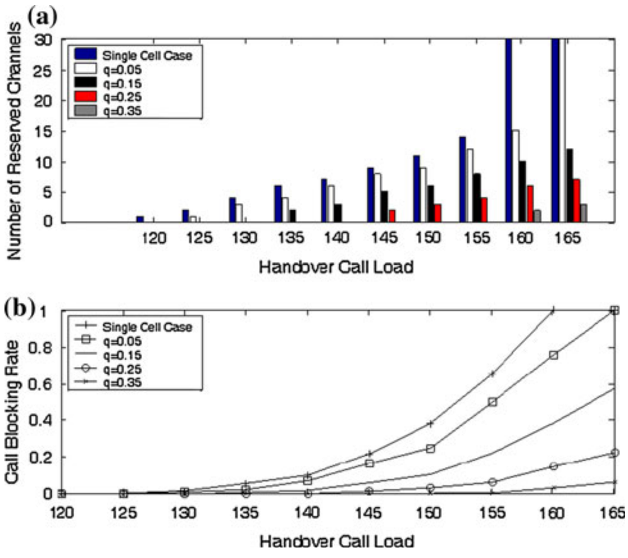

Fig. 5 Channel reservation

required HOD rate. In Part (a) of Fig. 5, 30 reserved channels stand for this case. With the increasing access probability, the channel reservation can be greatly decreased. In the case of $q = 0.35$, under most of the traffic load, there is no need for channel reservation to meet the HOD rate requirement. Part (b) of Fig. 5 shows the corresponding call blocking rate when the minimum reservation is applied. We can easily observe the great improvement especially when traffic load becomes heavier. Since we are using the model from [16], the 0 reservation in this simulation means that even there is no channel reserved for the handoff calls, the shared channels can still satisfy the required HOD rate.

7 Conclusion

Ad hoc links introduced to the cellular systems can bring great improvements in terms of handoff performance because they provide additional options for handoffs via multi-hop connections to BSs, leading to better service for roaming MNs by connecting to cells with more channel resource. The proposed scheme in this paper, ANHOA can assist MNs' handoffs by utilizing the self-organizing small-scale ad hoc networks. Better handoff choice can be made when there are multi-hop handoff alternatives. Moreover, with multi-hop connections, multiple cells can balance the traffic load and collaboratively serve users with better performance. In light of this, we have proposed a load balancing framework to enable resource sharing without specifically tying resource up for handoff calls. In so doing, we could mitigate the handoff call dropping while not affecting too much to the new calls. Simulation results verify the benefits of our schemes.

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Appendix

According to [16], HOD rate in a cutoff prioritized reservation system can be modeled as a finite-state Markov chain.

In Fig. 6, S_i denotes the state of i channels being occupied. λ_N and λ_{HO} stand for the arrival rate of new calls and handoff calls, respectively. C is the total number of channels and R is the number of reserved channels. μ is the departure rate for both types of calls. In this model, handoff calls and new calls start to use the shared channels when there are still spare channels in the shared channel pool. When the shared channels are used up, only handoff calls can use the reserved channels.

We can write the state equations as the follows.

$$P(i) = \begin{cases} \frac{\lambda_N+\lambda_{HO}}{i\mu} \cdot P(i-1), & \text{for } i = 1, 2, \ldots, C-R \\ \frac{\lambda_{HO}}{i\mu} \cdot P(i-1), & \text{for } i = C-R+1, \ldots, C \end{cases}$$

With the normalization condition, we can derive the probability of state 0.

$$P(0) = \left(\sum_{k=0}^{C-R} \frac{(\lambda_N + \lambda_{HO})^k}{k!\mu^k} + \sum_{k=C-R+1}^{C} \frac{(\lambda_N + \lambda_{HO})^{C-R} \lambda_{HO}^{k-C+R}}{k!\mu^k} \right)^{-1}$$

The HOD happen when all the channels are occupied. Therefore, the HOD rate is the probability of state C.

$$P_C = \frac{(\lambda_N + \lambda_{HO})^{C-R} \lambda_{HO}^{R}}{C!\mu^C} \cdot P(0) \qquad (11)$$

The call blocking probability is equal to the summation of probabilities that the states occupy state $C - R$ to state C.

$$P_B = \sum_{k=C-R}^{C} P(k). \qquad (12)$$

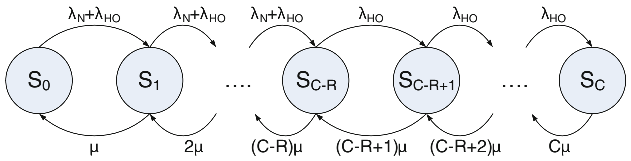

Fig. 6 Markov chain model for handoff reservation system

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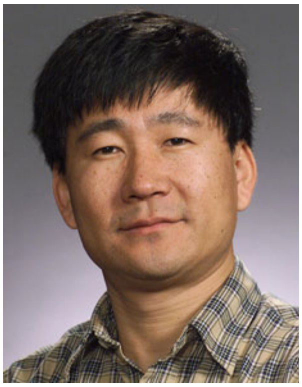

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