Power-Strength-Based Selective Forwarding (PSF) Mechanism for Multihop Cellular Networks

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Abstract—This paper presents a power-strength-based selective forwarding (PSF) mechanism to efficiently flood route requests (RREQs) during route discovery in multihop cellular networks (MCNs). In PSF, each mobile station utilizes the received power strength, instead of the connectivity or overhead information, to determine whether it has to be a forwarding participant or not. It reduces the signaling overhead and prevents unnecessary interference during route discovery. An analytical method is proposed to set the power thresholds required to ensure a target connectivity probability. The accuracy of the proposed method was verified via computer simulation. Simulation results show that the proposed PSF mechanism can significantly reduce the number of RREQs while ensuring the connectivity probability.

Index Terms—Efficient flooding, multihop cellular networks (MCNs), opportunity-driven multiple access (ODMA), selective forwarding.

I. INTRODUCTION

In recent years, there has been an upsurge of interest in multihop cellular networks (MCNs) [1], [2] in both industry and academia, such as the opportunity-driven multiple-access (ODMA) [3] concept proposed in the Third-Generation Partnership Project (3GPP) and the Multihop Relay technique developed in IEEE 802.16j [4]. An MCN is a cellular network that incorporates the multihop relaying technology [1]. Different from conventional one-hop cellular networks, the MCN splits the communication path from a base station to the mobile station into multiple shorter links by utilizing intermediate mobile stations or relay stations. By breaking a long-distance path into several short links, the path loss at each link can significantly be reduced, and thus, it provides an opportunity for performance improvement. The advantages of using MCNs include increasing the throughput of the network, enlarging the coverage area of the base station, decreasing the power consumption of the individual mobile station, and increasing the network scalability [1], [2].

The disadvantage of using MCNs is the extra signaling overhead resulting from link maintenance and route discovery. Unlike conventional one-hop cellular systems, a source node has to perform a route discovery procedure to identify the relaying nodes for establishing a path to the base station prior to data exchange. In pure mobile ad hoc networks (MANETs), routing is a very challenging issue due to the mobility of users and the lack of central control. Routing in MCNs, in contrast, is most likely to be more manageable, owing to the presence of a central controller (i.e., base station, which is the common source for downlink and the common destination for uplink transmissions) [5]. Nevertheless, routing is still a nontrivial issue in MCNs, owing to the presence of many candidate relaying nodes, and the selection of relaying nodes may directly impact the overall performance. The need of a routing algorithm in MCN normally introduces extra signaling overhead in broadcasting route information. The signaling overhead of the routing protocol results in some disadvantages in the implementation of MCNs. First, the signaling overhead introduces extra radio interference to the existing communications. The effect of the interference is normally ignored in MANETs but cannot be neglected in cellular networks. It is mainly because the transmission power of nodes in MCNs can be several orders of magnitude higher than that of nodes in MANETs. For example, the transmission power of nodes in Global System for Mobile Communications/wideband code-division multiple access/Worldwide Interoperability for Microwave Access based MCNs can be up to 1 or 2 W. In contrast, the transmission power of nodes in the Zigbee/WiFi-based MANET is about 10 or 100 mW. Second, the broadcasting nature of the signaling overhead may result in broadcast storm problem or acknowledgment problem [6]. Third, the signaling overhead may consume extra network resources and reduce the users’ battery life on standby. However, most of the existing routing protocols of MCNs (e.g., congestion-based routing [7], physical-distance-based routing [8], path-loss-based routing [6], transmission-power-based routing [9], and path-loss-with-transceiver-power-based routing [10]) focus on the selection of the optimal route. In most of the approaches, two-hop transmission with fixed relay nodes was assumed, and thus, the signaling overhead was normally ignored.

In the implementation, the complexity of an MCN is highly dependent on the amount of signaling overhead [7]. To effectively exploit the benefit of relaying while minimizing its disadvantages, well-designed routing algorithms with low signaling overhead are crucial, particularly for MCNs that utilize...
mobile stations as relay nodes and support $N$-hop transmission (i.e., $N > 2$). In this paper, a power-strength-based selective forwarding (PSF) method is presented to reduce the signaling overhead of the routing protocol in MCNs. An analytical model is presented to derive the parameters of PSF for a target connectivity probability (i.e., the probability for a mobile station to identify a path or route to the base station). To prove the effectiveness of the proposed method, a case study was carried out based on a time-division-duplexing code-division multiple-access (TDD-CDMA) system [7] with ODMA enhancement. The accuracy of the analysis is first verified via numerical results. The simulation results further show that the proposed method can ensure the connectivity probability with minimum signaling overhead.

The rest of this paper is organized as follows: In Section II, the background of this paper is presented, where a survey of the existing routing algorithms and efficient flooding mechanisms are briefly described. Section III presents the system model used in this paper. The proposed PSF method is then described in Section IV. Simulation studies and the relative advantages and limitations of the proposed mechanism are discussed in Section V. Conclusions are finally drawn in Section VI.

II. RELATED WORK

A. Routing Algorithms

In either MANETs or MCNs, the amount of signaling overhead mainly depends on the chosen routing algorithm. The routing algorithms in MANETs can generally be classified into two categories: 1) proactive routing and 2) reactive routing [11], [12]. Proactive routing mechanisms discover and calculate routes all the time. Each node periodically exchanges its routing information with its neighbors by continuously broadcasting hello/topology messages, and thus, its signaling overhead depends on the broadcasting interval and the number of nodes in the network. In contrast, reactive routing schemes find and maintain routes only when needed. The signaling overhead of reactive routing increases with the increasing number of active communication pairs as well as with the number of nodes [11], [12]. In MCNs, the radio resource is centrally controlled, and thus, a mobile station has to establish a connection with the base station before data are transmitted. In such an environment, reactive routing offers several advantages over proactive routing. First, reactive routing produces less signaling overhead, as there is no routing unless data transmission is required. Second, reactive routing only maintains necessary routing entries. Note that most of the routing entries maintained by proactive routing could be obsolete due to discontinuous reception (DRX) (i.e., a common technique used in a cellular network for prolonging the users’ battery life) [10] or users’ mobility.

In reactive routing, a source node normally utilizes flooding to deliver a route request (RREQ) packet to the destination. Once an RREQ reaches its destination, the destination reports a route response back to the source along the nodes that the RREQ has traversed. In case multiple RREQs are received, the route with the best performance metric would be reported. During the route-discovery phase, the RREQ can be broadcast to the entire network (i.e., complete flooding) or a certain part of it (i.e., scoped flooding). For example, dynamic source routing (DSR) [13] utilizes complete flooding to find a route to its destination if a source cannot reach the destination in a single hop. In contrast, ad hoc on-demand routing (AODV) [14] uses incremental scoped flooding to find a route. A source gradually enlarges the flooding diameter until it finds a destination or the search diameter reaches a predefined “time-to-live (TTL)” threshold (i.e., the maximum number of relay nodes in the routing path). AODV should use complete flooding if no route is found when the search diameter hits the threshold.

B. Efficient Flooding

Efficient flooding mechanisms have widely been used to reduce the number of forwarding participants and the flooded messages in MANETs. All the existing approaches try to select a minimal subset of forwarding nodes, called a dominant set, which is sufficient to deliver the flooding packet to every other node in the network. Two basic approaches are employed to select the dominant set: 1) clustering and 2) nonclustering [12].

The clustering approach improves the flooding efficiency by choosing gateway nodes (i.e., nodes that can hear more than one clusterhead) as forwarding participants. The clusterheads can be chosen by using either active clustering [15] or passive clustering [12] algorithms. In active clustering algorithms, each node has to periodically advertise cluster-dependent information for selecting clusterheads and gateways. Thus, it introduces extra signaling overhead and interference. The passive clustering technique [12] tries to build clusters by passively monitoring the cluster status carried by the users’ data packets. These clustering approaches rely on well-established clusters, which are not easy to construct and maintain in MCNs that enable DRX. In addition, the selection of clusterheads based on the overhead neighboring information may be meaningless in MCNs because each node can overhear packets transmitted from nodes that are far away from it. Therefore, the clustering-based approach is impractical for MCNs.

On the contrary, the nonclustering approach improves the flooding efficiency by excluding leaf nodes of a source tree [16] or a well-covered mesh [17] from forwarding participants. For example, Qayyum et al. [17] proposed a multipoint relaying mechanism to restrict the number of forwarding participants to a small set of neighbor nodes, instead of all neighbors, as in complete flooding. For a given node, the set is selected from the node’s neighbors that cover the same network region as the complete set of neighbors do. In these nonclustering approaches, complete one- and two-hop connectivity information is required to build the source tree or the well-covered mesh. Hence, a source node has to perform at least two complete flooding to collect the connectivity information [12]. The complete flooding itself may introduce extra signaling overhead and interference to the existing communications. In addition, the one- and two-hop connectivity information could also be meaningless for MCNs since almost all the nodes are within the two-hop transmission range of the others (i.e., each node is one hop away from the base station). Hence, the nonclustering-based approach cannot directly be applied in MCNs.
For MCNs that enable DRX, it seems that the reactive routing approach would be a better choice. Hence, the existing routing protocols proposed for MCNs normally adopt DSR to discover the best route. Some routing protocols further utilized a scoped flooding approach to reduce the signaling overhead of DSR. For example, Choi and Cho [6] proposed an inhibit access control method that utilized the path loss (or, equivalently, distance) to eliminate useless forwarding participants. Some approaches [10] further utilized the TTL threshold to limit the search diameter of each RREQ. Generally, the TTL threshold can be derived based on the given system-level constraints of MCNs. For example, the TTL threshold may depend on the maximum intracell interference [18], the end-to-end delay requirement of the multihop transmission [4], the maximum route-discovery time [6], or the performance metric of the routing protocol [10].

As learned from MANETs, the flooding efficiency of the protocols can further be improved by eliminating the number of forwarding participants. However, there are two main issues needed to be solved in designing efficient flooding algorithms in MCNs. The first issue is to set a proper transmission power for the node to relay the RREQs to minimize the intracell interference introduced by the RREQs. The second issue is to restrict the number of forwarding participants to maintain the (route) connectivity probability at an acceptable level. The solution of the two issues will be addressed in the following sections.

III. SYSTEM MODEL

In this paper, a 3GPP TDD-CDMA cellular system [7] with ODMA enhancement is illustrated. Each cell is equipped with an omnidirectional antenna at its base station (also referred to as Node B in 3GPP) and has several ODMA-enabled mobile stations (also known as user equipment (UE) in 3GPP). Each ODMA-enabled UE is identified by its user-specific identities. It is assumed that Node B may allocate dedicated timeslots for the multihop communication to minimize the power warfare problem [7] among ODMA and non-ODMA UEs. To simplify our description, we use the term “UE” to denote an ODMA-enabled UE in the rest of this paper. In the MCN, the UEs are categorized into three types: 1) SendingUE, 2) BackerUE, and 3) RelayUE. A SendingUE originates the multihop transmission. The other UEs that participate in route discovery within the cell are referred to as BackerUEs. Among these BackerUEs, some will be identified as RelayUEs, which are responsible for relaying data packets between SendingUE and Node B. Note that UEs that do not have sufficient residual power may optionally disable some relay functionalities (e.g., RREQ flooding) to reduce unnecessary power consumption.

Normally, the UEs in an MCN adopt scoped flooding methodologies (i.e., reactive routing with TTL constraint) [6], [10] to discover the best route to Node B. It is assumed that $d$ is the distance between SendingUE and Node B, and the TTL threshold of RREQ, which is denoted as $N_{opt}$, is given by the system-level constraints. For example, $N_{opt}$ can be derived based on the end-to-end delay constraint between a SendingUE and Node B. $N_{opt}$ can also be set to minimize the overall power consumption of the signaling messages flooded during route discovery [10]. For each flooding, it is further assumed that SendingUE shall find a route to Node B with probability no less than a target connectivity probability $P_{S,min}$. That is, $P_S \geq P_{S,min}$, where $P_S$ is the connectivity probability of each routing. The transmission radius (or, equivalently, transmission power) of the RREQ is set to be $d_{opt} + \Delta d$, where $d_{opt} = d/(N_{opt} + 1)$, and $\Delta d$ is a system parameter that can be calculated by Node B based on the estimated UE density and the given values of $N_{opt}$ and $P_{S,min}$.

Fig. 1 shows an MCN with several UEs, where UE$_j$ ($j = 1, \ldots, 12$) are BackerUEs, and $N_{opt} = 1$. The main concept of the existing scoped flooding methods [6], [10] is demonstrated in Fig. 1(a). In these methods, only nodes that are located in the region where the two big circles with radius overlap (i.e., UE$_i$, for $i = 1, \ldots, 8$) are chosen as forwarding participants [6]. For example, UE$_{11}$ and UE$_{12}$ are “bad forwarding participants” because they are not in the overlapped region. The power-efficient routing (PER) [10] method further suggests that no further forwarding is allowed if the TTL threshold is exceeded. In this case, UE$_6$ is a “bad forwarding participant” because its TTL threshold is exceeded. The signaling efficiency may be improved by eliminating those “bad forwarding participants,” as
illustrated in Fig. 1(b). In the following section, a PSF method is presented to eliminate these “bad forwarding participants.”

IV. POWER-STRENGTH-BASED SELECTIVE FORWARDING

In this section, the basic concept of PSF is first described, and an analytical method used to derive the control parameters is then described. Finally, the procedure required to adopt PSF to the PER method is illustrated.

The basic concept of PSF is illustrated in Fig. 1(b). It can be found that the signaling overhead of the PER can further be reduced by only selecting BackerUEs located in the shaded ring region (which is bounded by the two circles with radius $d_{\text{opt}} + \Delta d_+$ and $d_{\text{opt}} - \Delta d_-$, respectively) as BackerUEs. In this example, only UE $s$ is selected as the BackerUE for flooding RREQ to its neighbors. Note that the width of the ring is a tradeoff between the routing efficiency and the connectivity probability and, thus, should properly be assigned.

In PSF, the transmission radius of the RREQ flooded by SendingUE and intermediate UEs is fixed and set to be $d_{\text{opt}} + \Delta d_+$. In each flooding, only UEs located in the ring region bounded by the two circles with radius $d_{\text{opt}} + \Delta d_+$ and $d_{\text{opt}} - \Delta d_-$ are allowed to forward the RREQ. The flooding repeats until the RREQ reaches Node B or the RREQ has been forwarded by $N_{\text{opt}}$ BackerUEs. For ease of demonstration, the results of $\Delta d_+ = \Delta d_- = \Delta d$ are presented herein. The general cases that $\Delta d_+ \neq \Delta d_-$ can be derived in a similar manner; see Yang’s master thesis [19] for details.

The setting of $\Delta d$ depends on the UE density and affects the connectivity probability $P_S$. For example, one may increase $P_S$ by enlarging $\Delta d$. However, a large $\Delta d$ may increase the number of forwarding participants and the radio interference. In contrast, a small $\Delta d$ may eliminate unnecessary forwarding participants; however, it may result in a reduced connectivity probability because no route could be found if Node B fails to receive any RREQ. Hence, there is a tradeoff between $P_S$ and the signaling overhead.

In this paper, an analytical model is proposed to determine the $\Delta d$ required to achieve a target connectivity probability of $P_{S_{\text{min}}}$. Mobile wireless channels suffer from shadowing and fast fading. On the average sense, fast fading was ignored in the analysis. For analytical traceability, the shadowing effect was neglected in the analysis and will be examined in the simulation. The analytical model is developed based on the assumptions of uniformly distributed UEs in a single cell with a path-loss wireless channel. Note that the shadowing effect creates a new dimension of user diversity. Therefore, SendingUE may have more opportunities to find a path (or a higher connectivity probability $P_S$) than that obtained from the path-loss-only analytical model. Hence, the analytical results offer us a lower bound to achieve the target connectivity probability.

In the following, the case of $N_{\text{opt}} = 1$ is first studied, and the result is then extended for the cases of $N_{\text{opt}} = 2$ and $N_{\text{opt}} = 3$. Before going into detail, the parameters used in the following analysis are summarized as follows:

- $d$ Distance between SendingUE and Node B.
- $d'$ Distance offset resulting from the extra antenna gain of Node B.
- $N_{\text{opt}}$ Maximum number of RelayUEs in a multihop communication path.
- $P_S$ Connectivity probability, which is the probability that a SendingUE can find a path consisting of $N_{\text{opt}}$ RelayUEs to Node B.
- $P_{S_{\text{min}}}$ Target connectivity probability set by the network.
- $\Delta d$ Distance offset determined by PSF.
- $R'$ Transmission radius of the last-hop UEs considering the receiver antenna gain of Node B (i.e., $R' = R + d'$, which is the radius of the outer circle of the last-hop ring).
- $R$ Transmission radius of UE excluding the last-hop UEs for flooding RREQ (i.e., $R = d_{\text{opt}} + \Delta d$, which is the radius of the outer circle of the ring excluding the last hop).
- $r$ $r = d_{\text{opt}} - \Delta d$ is the radius of the inner circle of the ring.
- $A_s$ Set of possible locations of the $i$th RelayUE.
- $G_{r,\text{UE}}$ Receiver antenna gain of UE.
- $G_{r,\text{NB}}$ Receiver antenna gain of Node B.

In PER [10], the $d_{\text{opt}}$ is derived assuming that UEs and Node B have equal receiver antenna gain. However, the receiver antenna gain of Node B may be greater than that of UE. Hence, Node B may detect weaker signals than a UE does if all UEs forward the RREQ using the same transmit power. Thus, the last hop will be longer than the other hops while keeping the same interference level to UEs. The increased distance of the last hop (or, the distance offset resulting from the extra antenna gain of Node B), which is denoted as $d'$, can be determined based on the difference between the receiving antenna gain of Node B and that of a UE.

In this paper, the extra antenna gain of Node B is considered in the analytical model. Two options can be adopted in the implementation while considering the extra antenna gain of Node B. In the equal-transmit-power option, all UEs use the same transmit power to forward RREQ and relay data packets. In this option, the transmission distance of the last hop will be longer than the other hop due to the extra antenna gain. Therefore, the $d_{\text{opt}}$ derived from [10] needs to be modified by $d_{\text{opt}} = (d - d')/(N_{\text{opt}} + 1)$, where $d' = d - d'(G_{r,\text{NB}}/G_{r,\text{UE}} - 1)/(N_{\text{opt}} + \sqrt{G_{r,\text{NB}}/G_{r,\text{UE}}})$. In the equal-distance option, the last-hop UEs will use a lower transmit power than that used by the other UEs. The power ratio between the transmit power of last-hop UEs and that of the other UEs is equal to $G_{r,\text{UE}}/G_{r,\text{NB}}$. In this option, the transmission distance of all UEs is the same. Hence, $d_{\text{opt}}$ derived from [10] can be reused. The equal-distance option is the preferred approach in MCNs since it reduces the total power consumption of UEs.

In the following analysis, the analytical model is developed based on the equal-transmit-power option. However, it can easily be extended to accommodate the equal-distance option by setting $R' = R$.

- $A$ Area of the cell under investigation.
- $m$ Total number of registered UEs in the cell. Note that the UE density is equal to $m/A$ (unit: UEs/m²).
A. Single RelayUE: $N_{\text{opt}} = 1$, $d_{\text{opt}} = (d - d')/2$

Fig. 2 depicts the geometry model used to determine $P_S$ for $N_{\text{opt}} = 1$. In this case, SendingUE can find a route to Node B if there is at least one UE located in the area of $A_1$. Hence, the connectivity probability can be derived as

$$P_S = 1 - Pr\{\text{No UE in } A_1\} = 1 - \left(1 - \frac{A_1}{A}\right)^m.$$  \hfill (1)

As illustrated in Fig. 2, letting $x$ be the distance from a point in the shaded region to Node B, the area of $A_1$ can be calculated by

$$A_1 = 2 \int_{d-R}^{R'} x \cdot \cos^{-1} \left(\frac{x^2 + d^2 - R^2}{2xd}\right) \, dx.$$  \hfill (2)

Therefore, $\Delta d$ (or $R$ and $r$) can be obtained by solving (1) and (2) for given values of $P_S$, $A$, $m$, $d$, and $d'$ subject to the boundary condition $P_S \geq P_{S,\text{min}}$.

B. Two RelayUEs: $N_{\text{opt}} = 2$, $d_{\text{opt}} = (d - d')/3$

Fig. 3 shows the geometry model used to determine $P_S$ for $N_{\text{opt}} = 2$. In this case, SendingUE can find a route to Node B if there is at least one UE located in the area $A_1$ and at least one UE located in the area $A_2$. Hence, the connectivity probability can be derived as

$$P_S = 1 - Pr\{\text{(No UE in } A_1) \cup \text{(No UE in } A_2)\}$$

$$= 1 - \left(1 - \frac{A_1}{A}\right)^m - \left(1 - \frac{A_2}{A}\right)^m - \left(1 - \frac{A_1 + A_2}{A}\right)^m.$$  \hfill (3)

Since the first RelayUE should be located within the transmission range of $R$ from SendingUE, the distance from this RelayUE to Node B should be less than $R + R'$, which determines the region of $A_1$. The area of $A_1$ is given by

$$A_1 = 2 \int_{d-R}^{R'} x \cdot \cos^{-1} \left(\frac{x^2 + d^2 - R^2}{2xd}\right) \, dx - \int_{d-R}^{R+R'} x \cdot \cos^{-1} \left(\frac{x^2 + d^2 - r^2}{2xd}\right) \, dx.$$  \hfill (4)

Three criteria are used to determine $A_2$. First, the distances from the second RelayUE to SendingUE should not be greater than $2R$. Second, the distances from the second RelayUE to Node B should not be greater than $R'$. Third, the distance between the two RelayUEs should not be greater than $R$. Denote $\bar{d}_1$ as the mean distance from the first RelayUE in $A_1$ to Node B. $\bar{d}_1$ is shown in (5) at the bottom of the page. On the average, the boundary can be determined by the intersections of the two circles: one is centered at SendingUE with radius $R$, and the other is centered at Node B with radius $\bar{d}_1$. Therefore, the area of $A_2$ can be obtained as denoted in Fig. 3 and is given by

$$A_2 = 2 \int_{d_1-R}^{R'} x \cdot \cos^{-1} \left(\frac{x^2 + \bar{d}_1^2 - R^2}{2xd_1}\right) \, dx$$

$$+ \int_{d_1-R}^{d_1-R} x \cdot \cos^{-1} \left(\frac{d^2 + \bar{d}_1^2 - R^2}{2dd_1}\right) \, dx.$$  \hfill (6)

\begin{align*}
\bar{d}_1 &= \frac{\int_{d-R}^{R+R'} x^2 \cdot \cos^{-1} \left(\frac{x^2 + d^2 - R^2}{2xd}\right) \, dx - \int_{d-R}^{R+R'} x^2 \cdot \cos^{-1} \left(\frac{x^2 + d^2 - r^2}{2xd}\right) \, dx}{\int_{d-R}^{R+R'} x \cdot \cos^{-1} \left(\frac{x^2 + d^2 - r^2}{2xd}\right) \, dx - \int_{d-R}^{R+R'} x \cdot \cos^{-1} \left(\frac{x^2 + d^2 - r^2}{2xd}\right) \, dx} \tag{5}
\end{align*}
Similarly, $\Delta d$ can be obtained by solving (3)–(6) for given values of $A$, $m$, $d$, and $d'$ subject to the boundary condition $P_S \geq P_{S_{\text{min}}}$. 

### C. Three RelayUEs: $N_{\text{opt}} = 3$, $d_{\text{opt}} = (d - d')/4$

Fig. 4 illustrates the geometry model used to determine $P_S$ for $N_{\text{opt}} = 3$. Similarly, the connectivity probability can be derived as

$$P_S = 1 - \Pr \left( \text{(No UE in A)} \cup \text{(No UE in B)} \right)$$

$$= 1 - \sum_{k=1}^{3} (-1)^{k-1} S_k$$

where

$$S_k = \sum_{1 \leq i_1 < \cdots < i_k \leq n} [\Pr \left( \text{(No UE in A}_{i_1} \right) \cap \cdots$$

$$\cap \text{(No UE in A}_{i_k} \left) \right].$$

Since the first RelayUE should be located within the transmission range of $R$ from SendingUE, the distance from this RelayUE to Node B should be less than $2R + R'$, which determines the region of $A_1$. The area of $A_1$ is given by

$$A_1 = 2 \left[ \int_{d-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + d^2 - R^2}{2xd} \right) dx - \int_{d'-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + (d + d')^2 - R^2}{2xd} \right) dx \right].$$

Denote $\bar{d}_1$ and $\bar{d}_2$ as the mean distance from the first RelayUE in $A_1$ and the second RelayUE in $A_2$ to Node B, respectively, as shown in (10) and (11) at the bottom of the page.

The areas of $A_2$ and $A_3$ can be obtained from Fig. 4 and are given by

$$A_2 = 2 \left[ \int_{d_1-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + \bar{d}_1^2 - R^2}{2xd_1} \right) dx + \int_{d_1-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + \bar{d}_1^2 - R^2}{2dd_1} \right) dx \right].$$

$$A_3 = 2 \left[ \int_{d_2-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + \bar{d}_2^2 - R^2}{2xd_2} \right) dx + \int_{d_2-R}^{R'} x \cdot \cos^{-1} \left( \frac{x^2 + \bar{d}_2^2 - R^2}{2dd_2} \right) dx \right].$$

Similarly, $\Delta d$ can be obtained by solving (7)–(13) for the given values of $P_S$, $A$, $m$, $d$, and $d'$, subject to the boundary condition $P_S \geq P_{S_{\text{min}}}$. The results can be extended to accommodating the cases of $N > 3$ RelayUEs, where $N > 3$. The connectivity probability
\begin{equation}
P_S = \begin{cases} 
1 - \left(1 - \frac{A_i}{A}\right)^m, & \text{for } N = 1 \\
1 - \sum_{i=1}^{N} \left(1 - \frac{A_i}{A}\right)^m + \left(1 - \frac{A_1+A_2}{A}\right)^m, & \text{for } N = 2 \\
1 - \sum_{i=1}^{N} \left(1 - \frac{A_i}{A}\right)^m + \left(1 - \frac{A_1+A_2}{A}\right)^m + \sum_{i=1}^{N-1} \left(1 - \frac{A_{i+1}}{A}\right)^m - \left(1 - \frac{1}{A}\right)^m, & \text{for } N \geq 3.
\end{cases}
\end{equation}
\text{(14)}

The area of \(A_i, \ i = 1, \ldots, N\), can be derived in a similar manner. However, owing to space limitations, details of the derivation are not elaborated upon herein.

D. Implementation Considerations

In the foregoing derivations, the distance is used to obtain \(P_S\). In the implementation, each UE may utilize Friis free-space equation [20] to estimate the distance between the UE and a given transmitter. Denote \(D\) as the distance between a transmitter and a receiver. \(D\) is estimated by

\begin{equation}
D = \frac{\lambda}{4\pi} \sqrt{\frac{G_t G_r P_{TX}}{L P_{RX}}}, \Delta \sqrt{\frac{P_{TX}}{k P_{RX}}}
\end{equation}
\text{(15)}

where \(P_{TX}\) is the transmit power of the transmitter, \(P_{RX}\) is the received power measured at the receiver, \(G_t\) is the antenna gain of the transmitter, \(G_r\) is the antenna gain of the receiver, \(\lambda\) is the wavelength of the carrier signal, \(n\) is the power-law attenuation factor (i.e., \(4 \geq n \geq 2\)), \(L\) is the system loss factor (i.e., \(L \geq 1\)), and \(k\) is equal to \((4\pi)^n L/\lambda^n G_t G_r\).

In mobile cellular networks, Node B will regularly send a broadcast channel (BCH), announcing the access parameters of the cell. Let \(P_{BCH}\) and \(P_{avg}\) be the BCH power transmitted by Node B and the received power of \(SendingUE\) averaging within a number of BCH intervals, respectively. In a Universal Mobile Telecommunications System, \(P_{BCH}\) is a constant and is periodically broadcast by Node B. Hence, \(SendingUE\) can estimate \(d\) from (15) and report it back to Node B during the access phase, and

\begin{equation}
d = \sqrt{\frac{P_{BCH}}{k_{N-U} P_{avg}}}
\end{equation}
\text{(16)}

where \(k_{N-U}\) is the parameter related to Node B-to-UE transmission, which is equal to \((4\pi)^n L/\lambda^n G_{t, NB} G_{r, UE}\), and \(G_{t, NB}\) is the transmitter antenna gain of Node B.

Note that \(P_S\) is a performance parameter set by the network operator, \(A\) is a constant representing the coverage area of a cell, \(m\) is the number of registered (or attached) UE, and \(N_{opt}\) is determined from Lemma 1 of PER [10]. All four parameters are known by Node B. Hence, Node B can calculate \(\Delta d\) from the given values of \(P_S, A, m, \) and \(N_{opt}\), and the distance \(d\) reported by \(SendingUE\), and, thus, determine the transmission power of each RREQ. The transmission power of the RREQ, which is denoted as \(P_{RREQ}\), needs to cover a transmission radius of UE and is given by

\begin{equation}
P_{RREQ} = k_{U-U} P_{min} R^n = k_{U-N} P_{min} (R + d')^n
\end{equation}
\text{(17)}

where \(P_{min}\) is the minimum power required by a UE to correctly decode the RREQ, \(k_{U-U}\) is the parameter related to UE-to-UE transmission, which is equal to \((4\pi)^n L/\lambda^n G_{t, UE} G_{r, UE}\), \(k_{U-N}\) is the parameter related to UE-to-Node B transmission, which is equal to \((4\pi)^n L/\lambda^n G_{t, UE} G_{r, NB}\), and \(G_{t, UE}\) is the transmitter antenna gain of UE.

Note that \(P_{min}\) could properly be set by considering the effects of shadow fading and multipath in the implementation. Node B will announce \(P_{RREQ}\) to \(SendingUE\) and all \(BackerUE\)s during the access phase such that all UEs can use \(P_{RREQ}\) to perform selective forwarding.

In PSF, the \(BackerUE\)s that are located in the shaded region \(A_i\) are the possible candidates for the \(i\)th \(RelayUE\) and thus have to forward the RREQ if the hop-count limitation is not exceeded. However, it is not easy for a \(BackerUE\) to identify its location if it does not have a Global Positioning System (GPS). Even if each \(BackerUE\) is equipped with a GPS, it is still difficult for Node B to announce the boundary of the shaded region \(A_i\) directly. Hence, two approaches are proposed to implement the concept of selective forwarding.

**Approach I:**

**Approach I** adopts a similar scoped flooding concept adopted by PER. That is, each \(BackerUE\) utilizes the measured power level of every received RREQ to decide whether to forward the RREQ or not. Let the measured power level of the \(j\)th RREQ received by \(BackerUE_i\) be \(P_i\) and the power level of an RREQ received at a distance of \(R\) and \(r\) from the transmitter be \(P_r\) and \(P_{r'}\), respectively. \(P_r\) and \(P_{r'}\) are given by

\begin{equation}
P_r = \frac{P_{RREQ}}{k R^n} = P_{min}
\end{equation}
\text{(18)}

\begin{equation}
P_{r'} = \frac{P_{RREQ}}{k r^n} = P_{min} \left(\frac{R}{r}\right)^n.
\end{equation}
\text{(19)}

Hence, \(BackerUE_i\) will forward the \(j\)th received RREQ if and only if

\begin{equation}
P_r \geq P_{r'} \geq P_r.
\end{equation}
\text{(20)}

**Approach I** can achieve the same connectivity probability set by (14). However, it still results in many unnecessary RREQs, as illustrated in Fig. 5(a). Hence, **Approach II** is further proposed.

**Approach II:**

In **Approach II**, each \(BackerUE\) utilizes the measured power levels of \(SendingUE\) and Node B to estimate its relative position and then to determine whether to act as a \(RelayUE\) or not individually. Denote \(d_{N,i}\) and \(d_{S,i}\) as the distance from \(BackerUE_i\) to Node B and to \(SendingUE\), respectively. In this approach, \(BackerUE_i\) should act as a \(RelayUE\) and is responsible for forwarding all of the received RREQs if and only if

\begin{equation}
\max\{q - 1\} R, r\} \leq d_{S,i} \leq q R
\end{equation}

\begin{equation}
d_{N,i} \leq (N - q + 1) R
\end{equation}

are both satisfied, where \(q \in (1, \ldots, N)\).
In other words, BackerUE_i is a candidate of the qth RelayUE. Note that for a given value of q, the region bound by (21) and (22) is slightly larger than A_q in (14). Thus, the connectivity probability obtained by the second approach is higher than P_S. As demonstrated in Fig. 5(b), Approach II may further reduce the unnecessary RREQs produced by the first approach.

E. PER With PSF Enhancement

The proposed PSF can reduce the signaling overhead for existing routing algorithms proposed for MCNs. As a demonstration, a case study named PER was carried out based on a reactive routing algorithm developed for MCNs [10]. The PER is proposed for a SendingUE to identify a minimum-power path to Node B in multihop communication. Prior to the route (or path) discovery, the PER mechanism utilizes an analytical method to estimate the total power and the number of intermediate UEs (i.e., N_opt) required in the minimum-power path. Based on the estimation, the PER may set TTL for each flooded RREQ to reduce the signaling overhead required during path discovery. It was shown in [10] that the PER mechanism can identify the same minimum-power path discovered by the DSR but with reduced signaling overhead.

The signal overhead can further be reduced by adopting PSF. Fig. 6 shows a scenario illustrating the message flows of PER with PSF enhancement adopting the network topology illustrated in Fig. 1(b). Approach II of PSF is used as an example. As mentioned, PER utilizes scoped flooding to reduce the number of RREQs. In this example, UE_{12} cannot receive the multihop service request from SendingUE, and UE_9, UE_{10}, and UE_{11} cannot receive the confirmation from Node B; hence, these BackerUEs do not participate in the route-discovery procedure. The RREQ message traversing along SendingUE–UE_7–UE_6 is discarded by UE_3 because N_opt is reached. The procedure describing the message flow shown in Fig. 6 is summarized as follows:

**Step 1.** Prior to communicating with Node B, the SendingUE UE_1 performs an open-loop power-control procedure, adjusts its transmission power to P_{RREQ}, and then sends an RRC_Connection_Req carrying P_{RREQ} to Node B. In this example, Node B derives that N_opt = 1 according to the rule specified in PER.

**Step 2.** BackerUE_i estimates its distance from SendingUE d_{S,i} according to P_{RREQ} and the received power strength of the overhead RRC_Connection_Req message.
Fig. 6. Message flow of the PER with PSF enhancement.

**Step 3.** Upon receiving the RRC_Connection_Req message, Node B acknowledges an RRC_Connection_Res message to SendingUE.

**Step 4.** BackerUE estimates its distance from Node B $d_{N,i}$ according to the received power strength of the overheard RRC_Connection_Res message.

**Step 5.** SendingUE adjusts its transmission radius to $R$ and sends RREQ to its neighboring UEs.

**Step 6.** Only BackerUE will forward the received RREQ since both (21) and (22) are satisfied.

**Step 7.** Node B determines the optimal routing path according to any predetermined performance metric.

**Step 8 and 9.** Node B sends an RRC_Connection_Setup message along the selected routing path to SendingUE. The multihop communication path is then established.

**F. Other Issues**

In this section, issues of mobility, intercell interference, and measurement error were addressed.

**Mobility:**

As in PER [10], PSF selects RelayUEs from stationary UEs. High-speed UEs are not preferred due to the high signaling overhead required for maintaining the multihop links. The attainable multihop communication gain may also be reduced since the distance between adjacent mobile RelayUEs may be increased due to movement. However, mobility is inevitable in MCNs. The mobility may affect the performance of the proposed PSF scheme. Let $d(t)$ be the distance between SendingUE and Node B measured at time $t$. $d(t)$ is a function of $t$ and mobility (for example, the speed and direction of the move). Assume that SendingUE issues the service request at $t = t_0$ and sends its RREQ at $t = t_1$. Note that $t_1$ depends on the processing speed of Node B. The impact of mobility to two implementation approaches is different. In Approach I, each BackerUE makes the forwarding decision based on the power level estimated from the currently received RREQ (i.e., $t > t_1$). Hence, $P_S$ will be decreased if $d(t_1) > d(t_0)$ since some of the RREQs sent by last-hop BackerUEs may fail to reach Node B. Similarly, $P_S$ will be increased if $d(t_1) < d(t_0)$ because Node B can receive more RREQs sent by last-hop BackerUEs. In Approach II, in contrast, each BackerUE makes the forwarding decision according to its relative position estimated at time $t_0$. Therefore, $P_S$ may always be decreased if $d(t_1) \neq d(t_0)$ since part of BackerUEs in the shaded regions identified by (21) and (22) at $t_0$ may move out of the regions at $t_1$.

The proposed PSF can still be applied if mobile UEs are considered. In this case, the mobility information (for example, the speed and direction of the move) of each UE will be assumed to be perfectly known [21]. Hence, each UE may predict the average received power at the time of interest [22] based on instantaneously measured power and its mobility information. Therefore, the same PSF mechanism can still be used to decide whether to forward an RREQ or not. However, the decision is then made based on the received power at the time of interest instead of the instantaneously measured power.

**Intercell Interference:**

The upper bound of the intercell interference resulting from the RelayUEs selected by the PSF is estimated as follows. Let $x_i$ be the minimum distance from the $i$th hop RelayUE to the nearest neighboring Node B. $x_i$ is given by

$$x_i = d_{ISD} - (N_{opt} - i)R - R'$$

where $d_{ISD}$ is the intercell distance. In PSF, $P_{RREQ}$ is the maximum transmission power of RelayUE. The maximum intercell interference resulting from the $i$th hop RelayUE is given by

$$I_{inter,i} = \frac{P_{RREQ}}{kx_i^n} = P_{min} \left( \frac{R}{d_{ISD} - (N_{opt} - i)R - R'} \right)^n.$$  

(24)
Note that $d_{ISD} - R' \geq 2(N_{opt}R + R') - R'$ and $R' \geq R$. Hence, the intercell interference is bounded by

$$I_{inter,i} \leq P_{\min}\left(\frac{1}{N_{opt} + i - 1}\right)^n.$$  \hspace{1cm} (25)

**Measurement Error:**

The estimation error of the measured power due to fading is a common problem for algorithms that utilize the measured power as a performance metric. Most of the wireless routing algorithms neglect this error and assume that the measured power is accurate enough to make decisions. As an example, DSR, AODV, and PER rely on the measured power of each link to determine the minimum power path. The same assumption was adopted in this paper. Several methods have been proposed to deal with the measurement error of the received power required for power control or dynamic channel allocation [22]. However, most of the approaches rely on results obtained from past measurements to reduce the estimation error. In PSF, the received power of each UE is obtained from a single measurement. A similar concept can be adopted here by performing route discovery several times. However, the accuracy of the measured power is obtained at the cost of increased signaling overhead. The tradeoff between the estimation accuracy and the signaling overhead will be the subject of future work.

**V. Simulation Results**

Simulations were conducted to verify the effectiveness of the proposed PSF mechanism. In the simulations, performance metrics of the connectivity probability, the total number of RREQs, and the total transmission power were used. The connectivity probability is used to validate the accuracy of the analytical model. The number of RREQs is used to evaluate the efficiency of the selected routing algorithms. The total transmission power is used to demonstrate the power efficiency of the different routing algorithms. In the simulations, the equal-distance option was assumed, and the ratio of the antenna gain of Node B and that of UE $G_{r, NB}/G_{r, UE}$ was set to be 2.

Four scenarios were considered in our simulation. In the first scenario, the connectivity probabilities achieved by PSF for different UE densities under a path-loss wireless channel were investigated. The analytical result of $\Delta d$ for different UE densities was also presented. The results are shown in Figs. 7 and 8. In the second scenario, the total number of RREQs required by the scoped routing algorithm and the two approaches of PSF for various UE densities under a path-loss wireless channel were compared. Note that the same value of $\Delta d$ was used for all of the three routing algorithms to have a fair comparison. The result is shown in Fig. 9. In the third scenario, the effect of shadow fading was examined, and the result is shown in Figs. 10 and 11. In the simulation, the total number of RREQs and the resulting connectivity probability for different shadowing factors were considered. In the last scenario, the total power used to transmit RREQ in all of the three routing algorithms for different shadowing factors was evaluated. It was designed to evaluate the intercell interference resulting from the signaling overhead and to investigate the power efficiency of the routing algorithms.

A snapshot-based simulation was conducted on an ns-2 simulator [23]. A single cell with 40–100 UEs was considered in the simulations. All UEs were assumed to be uniformly distributed within an area with size $1 \text{ km}^2$. It was assumed that Node B sets two power levels for flooding the RREQs, and the lower power level is used by the last-hop UEs. Hence, $d = 0$. The following parameters were used in the simulation: $d = 600 \text{ m}$, $N_{opt} = 3$, and $d_{opt} = 150 \text{ m}$. In all cases, $\Delta d$ (or, equivalently, $\Delta P$) is adjusted by solving (9)–(13) to guarantee a target connectivity probability of 0.9 (i.e., $P_{S,\min} = 0.9$). In the simulation, each
outcome was obtained from the routing result generated by ns-2. Each sample shown in the figure was obtained by averaging 10,000 outcomes. For each outcome, the signaling overhead of RREQs generated by three methods (i.e., PER, PER with PSF enhancement Approach I, and PER with PSF enhancement Approach II) were investigated. In PER, RREQs are flooded only in a scoped region, where the two big circles overlap, as shown in Fig. 1(a). For a fair comparison, the hop-count limitation and the transmission radius of PER were set to be the same as $N_{\text{opt}}$ and $d_{\text{opt}} + \Delta d$, respectively, as that used in PSF.

The wireless channel without shadow fading was first investigated. In this case, all of the three methods resulted in the same connectivity probability. The accuracy of the numerical analysis is first demonstrated in Fig. 7. The attainable $P_S$ of the three methods for different UE densities was shown. In this figure, the numerical results were indicated by a solid line. The mean values of the simulation results were marked by solid diamonds. It is found that the simulation results coincided with the numerical analysis for different UE densities, which verifies the accuracy of the analysis. In all cases, a target connectivity probability of $P_{\text{S, min}} = 0.9$ was always ensured. As illustrated in Fig. 8, PSF eliminates unnecessary flooding by adjusting the value of $\Delta d$. Hence, $\Delta d$ decreases as the UE density increases.

Fig. 9 demonstrates the total number of flooded RREQs, which is denoted as $N_{\text{RREQ}}$, required by PER, Approach I, and Approach II. In this figure, $N_{\text{RREQ}}$ of PER, Approach I, and Approach II of PSF were marked by solid circles, solid squares, and solid triangles, respectively. In all of the three methods, $\Delta d$ was set as shown in Fig. 8. In the simulation, all of the three methods can identify the same best routing path (i.e., the path that has the minimum total transmission power). However, their signaling overheads were quite different. The signaling overheads of PER and Approach I were both increased as the UE density increases since each forwarding in the two methods was decided based on the measured power of the received RREQ. In contrast, $N_{\text{RREQ}}$ is almost invariant to the UE density in Approach II since each forwarding was determined based on the relative position of the UE. The major difference between PER and Approach I is that fewer UEs are allowed to forward RREQ in Approach I, owing to a smaller shaded region. In Fig. 9, it is found that the difference of $N_{\text{RREQ}}$ generated by PER and Approach I is imperceptible for low UE density but is observable when the UE density increases because that PER has a larger shaded region and thus generates more RREQs. Note that, for a fixed $d_{\text{opt}}$, the difference between a circle (i.e., PER) and a ring (i.e., Approach I) depends on $\Delta d$. However, $\Delta d$ was a function of UE density, as shown in Fig. 8. The difference is small for low UE density (i.e., large $\Delta d$) but becomes significant for high UE density (i.e., small $\Delta d$). It was found that the flooding overhead of Approach II is 20.2% and 23.6% lower than that in PER and Approach I, respectively, for a given 90% connectivity probability in a high UE density environment. The performance improvement will be significant when the cell radius, the UE density, or the number of relaying nodes in a single path increases.

The impact of shadowing effects on PSF was then investigated, and the results are shown in Figs. 10–12. In the following simulations, the UE density of $10^{-4}$ UEs/m$^2$ was considered (i.e., one cell with 100 UEs). A log-normal distribution with standard deviations (i.e., shadowing factors) ranging from 2 to 12 dB was used to model the shadowing effect. Note that the shadowing factor of 0 dB refers to the results without shadowing effect. In the following simulations, it is found that Approach I achieves a connectivity probability that is almost identical to PER but with fewer signaling overhead, and Approach II always results in the lowest signaling overhead.
Fig. 10 demonstrates the $N_{RREQ}$ generated during route discovery for different shadowing factors. It was found that the impact of shadow fading to the signaling overhead of both PER and Approach I is significant. $N_{RREQ}$ of PER and Approach I were both increased as the growth of shadowing factor. The number of flooded RREQs in PER may even exceed the total number of UEs in the cell, which means that each UE may flood more than one RREQ. It is because that a larger shadowing factor results in a larger transmission radius for some RREQs, which means that more UEs will participate in the route discovery. In contrast, Approach II was less susceptible to shadow fading since $N_{RREQ}$ was almost invariant to the shadowing factor. However, the price paid is that the connectivity probability may not be as high as PER in the shadow environment.

Fig. 11 shows the connectivity probability achieved by the three methods for different shadowing factors. The target connectivity probability of 0.9 was always guaranteed for different shadowing factors. In comparison with the case without shadow fading, all of the three methods achieved higher connectivity probabilities due to the shadowing effect in most of the shadow environments. The connectivity probabilities of the three methods were first increased and then decreased as the shadowing factor increased. It is because that the increased RREQs offer extra chances to find alternative paths in a shadowing environment. PER and Approach I can find almost the same best route in the simulations and, thus, has a very similar connectivity probability. The only difference between PER and Approach I is that Approach I eliminates useless flooding by reducing the shaded region and, thus, resulted in a lower signaling overhead. The total transmission power required to flood the RREQs is illustrated in Fig. 12. In this figure, the transmit power of the last-hop UEs was set to be 3 dB less than that of the first two-hop UEs due to the extra antenna gain of Node B. It was found that PSF is a power-efficient solution under various shadowing environments. Hence, the adoption of PSF may help to extend the battery life for UEs in such a UE-assisted relay network.

VI. CONCLUSION

This paper has presented a PSF mechanism to reduce the signaling overhead for existing routing algorithms in MCNs. An analytical method was proposed to derive the transmission power used by each UE to flood its RREQ based on a target connectivity probability. It was demonstrated that the concept of PSF can be applied to further reduce the signaling overhead of the PER routing algorithm [10]. Two simple approaches were further presented to implement the proposed PSF mechanism. Simulation results demonstrated the accuracy and the superiority of the proposed PSF mechanism. The proposed PSF mechanism can always guarantee the target connectivity probability for a variety of UE densities. It can also work in a wireless channel without or with shadow fading. Approach I achieves almost the same connectivity probability as PER but with a lower signaling overhead. Approach II achieves the lowest signaling overhead among the three methods, and the signaling overhead is almost invariant to the environment (i.e., UE density and shadowing factor).

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their valuable comments, which have helped to improve the quality of this presentation.

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