Power-Efficient Routing Mechanism for ODMA Systems

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***Abstract*—Opportunity driven multiple access (ODMA), a cellular multihop method proposed for Universal Mobile Telecommunications Systems, potentially allows reduction in power consumption of user equipment (UE), extending Node B's coverage and supporting higher user data rate. However, ODMA requires extra power for discovering relaying nodes and introduces additional transmission latency in data transfer. This paper offers enlightenment to these ODMA implementation problems. A power-efficient routing (PER) mechanism is proposed to identify a minimum-power path for ODMA communication. Prior to the route (or path) discovery, the PER mechanism utilizes an analytical solution to estimate the total power and number of intermediate UEs required in the minimum-power path. With the estimation, route discovery procedures originating from nonattainable ODMA requests can be prevented. For those attainable ODMA requests that require a route discovery procedure to locate intermediate UEs, the PER mechanism further provides a method to set the transmission power and maximum hop count. Hence, the power consumption of each UE during route discovery is significantly reduced. Simulation results coincided with the analysis, and the results demonstrate the performance improvement of PER over dynamic source routing.**

***Index Terms*—Opportunity driven multiple access (ODMA), power-efficient routing (PER).**

I. INTRODUCTION

OPPORTUNITY driven multiple access (ODMA) is an *ad hoc* multihop relaying protocol [1] considered by the third-generation partnership project (3GPP) working group [2]. Although it has now been dropped to achieve a finalized standard as a result of concerns over complexity, battery life of users on standby, and signaling overhead issues, ODMA remains an attractive prospect for future mobile communication systems [3]. The advantages of ODMA include 1) potentially reduced transmission power; 2) possibly enhanced coverage; 3) increased capacity under certain circumstances; and 4) a greater tradeoff between quality-of-service (QoS) and capacity in the extended coverage areas [3], [4].

In ODMA, user data are exchanged between a sending mobile station [also known as user equipment (UE) in Universal Mobile Telecommunications System (UMTS)] and the base station (called Node B in UMTS) by being relayed through other intermediate UEs. The sending UE should establish a path through the intermediate UEs to Node B prior to data exchange, which introduces additional signaling overhead and thus results in extra power consumption for certain UEs. Hence, a good routing mechanism with low signaling overhead would be essential while realizing ODMA. Unlike mobile *ad hoc* networks (MANETs) [5] where communication generally occurs between any pair of nodes through several mobile relaying nodes, a sending UE in ODMA always exchanges data with Node B by utilizing nonmobile or low-mobility intermediate UEs [4]. Moreover, most of the nodes in MANET cannot directly communicate with each other due to the limited transmission power. However, all UEs in ODMA can communicate with Node B directly. Hence, existing routing methods proposed for MANET may not be directly applicable to ODMA.

Several power-aware routing methods [6]–[10] have been proposed for MANET and ODMA cellular networks. Most of the proposed methods are developed out of the dynamic source routing (DSR) protocol [11] and the *ad hoc* on-demand distance vector (AODV) routing protocol [12]. In DSR and AODV, the source node initiates a route discovery procedure by flooding a route request (RREQ) packet its surrounding nodes. The RREQ is always forwarded by intermediate nodes until the destination node is reached. The destination node sends back a route reply (RREP) packet carrying the power metrics of the selected path(s) to the source node. A minimum-power path is then identified based on the collected metrics. The power consumption of nodes in MANET was first considered by Singh *et al.* [6] in their routing method. Chang and Tassiulas [7] considered the residual power of UEs in their energy-efficient routing algorithm. Rodoplu and Meng [8] proposed a position-based routing method for mobile wireless networks. This method constructed a position-based sparse graph for all communication links connecting mobile nodes and then derived a minimum-power routing topology from the graph. Wattenhofer *et al.* [9] proposed a distributed topology control algorithm for MANET. Using the directional antenna technology, each UE constructed a communication graph, removed the nonefficient edges from the graph, and derived a minimum-power routing topology. The Vodafone Group [10] proposed an ODMA routing procedure where the given local and end-to-end connectivity information was utilized to construct the routing path.

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Three significant assumptions are made in the above proactive routing approaches. The first assumption is that each node retains the up-to-date location information and/or power metrics of the other nodes. This assumption may be effective in MANET but is not suitable for mobile cellular networks that enable the discontinuous reception (DRX) function. With DRX, a UE is in sleep mode for most of the time to save power and periodically wakes up to gather system information. Hence, each UE in a mobile cellular network cannot have up-to-date information of other UEs because all information would be obsolete after returning to sleep mode. This assumption may be relieved by employing reactive routing approaches [13]. However, existing reactive routing approaches rely on a route discovery procedure to obtain the other UEs' information. Hence, some routing control messages may be wasted on processing nonattainable ODMA requests (i.e., the power or latency requirement for those requests cannot be attained by utilizing the ODMA technology). The second assumption is that the extra power used by RREQ signaling is ignored. Therefore, RREQ in MANET is always flooded among UEs with UE's maximum transmission power and without hop count limitation. UE's transmission power can be up to several watts in a mobile cellular network, which cannot be neglected. The third assumption is that the power metric only considers the path loss between two adjacent UEs but neglects the power consumed by UEs' receivers.

This paper presents a power-efficient routing (PER) mechanism and identifies parameters required to discover a minimum-power path for ODMA communication. Different to the existing reactive routing approaches, the PER mechanism utilizes an analytical solution to estimate the total power (i.e., including the power consumed by UEs' receivers) and number of intermediate UEs required in the minimum-power path prior to route discovery. With the prediction, route discovery procedures originating from nonattainable ODMA requests can be prevented. For those attainable ODMA requests that require a route discovery procedure to locate intermediate UEs, the PER mechanism further provides a method to set the transmission power and maximum hop count when forwarding RREQ. With these settings, the power consumption of each UE during the route discovery can be significantly reduced.

The rest of this paper is organized as follows. Section II proposes the PER mechanism and discusses its key parameters and the effect of the parameters on system performance. Section III investigates the performance of the PER mechanism via numerical analysis and simulation. Conclusions are finally drawn in Section IV.

II. PER MECHANISM

A time division duplex (TDD)-ODMA network [3] comprising of Node B and several nonmobile ODMA-enabled UEs, which are identified by their user-specific identities (ODMA_IDs), is considered herein. It is assumed that Node B may allocate dedicate timeslots for the ODMA communication to minimize the power warfare problem [3] among ODMA and non-ODMA UEs. To simplify our description, we use the term "UE" to denote an ODMA-enable UE. In an ODMA transmission, the UEs are categorized into three types, namely 1) *Sending*UE; 2) *Backer*UE; and 3) *Relay*UE. A *Sending*UE originates the ODMA transmission. The other UEs that participate in the ODMA route discovery within the cell are *Backer*UEs. Among these *Backer*UEs, some will be identified as *Relay*UEs, which are responsible for relaying data packets between the *Sending*UE and Node B. Note that UEs that do not have sufficient residual power may optionally disable some ODMA functionalities to reduce unnecessary power consumption.

This study considers three power consumption modes of the UE, including sleep (SLP), receive (RX), and transmit (TX). In SLP mode, the UE consumes the least amount of power for running a timer. In RX mode, the receiver is turned on, and the UE can receive data from other UEs and Node B. In TX mode, the transmitter is turned on, and the UE can adjust its transmission power while transmitting data. The parameters used in the PER mechanism are defined as follows.

- P_{ref} and αP_{ref} are the minimum and maximum powers consumed by the UE in TX mode, respectively. βP_{ref} is the average power consumed by the UE in RX mode. γP_{ref} is the average power consumed by the UE in SLP mode. α, β, and γ are constant numbers and with the relationship $\alpha > 1 > \beta \gg \gamma > 0$ [1].
- $P_{\mathrm{TX\_RDP}}$ is the transmission power consumed by the UE when forwarding RREQ in the "path discovery phase."
- $N_{\max}$ is the maximum hop count that an RREQ can traverse in the "path discovery phase." N_{opt} is the number of *Relay*UEs required in an optimal path. The optimal path exists when the *Relay*UEs can be found at any location within a cell.
- $P_{\mathrm{total},i}$ is the total power required by the ith path discovered in the "path discovery phase." P_{opt} is the total power required in the optimal path. Note that $P_{\mathrm{total},i} \geq P_{\mathrm{opt}}$.
- P_{ini} is the transmission power consumed by the *Sending*UE to send the ODMA service request.

The PER mechanism consists of three phases, namely 1) access phase; 2) path discovery phase; and 3) path setup phase. In access phase, the *Sending*UE adjusts its transmission power to P_{ini} and sends an ODMA service request carrying P_{ini} to Node B. Node B can predict P_{opt} and N_{opt} based on P_{ini}. By using the predicted P_{opt} and N_{opt}, Node B checks whether the ODMA request is attainable or not. For nonattainable ODMA requests, Node B simply terminates the PER procedure by replying a rejection message to the *Sending*UE. For attainable ODMA requests, Node B further derives $P_{\mathrm{TX\_RDP}}$ and $N_{\max}$, and sends a confirmation message carrying $P_{\mathrm{TX\_RDP}}$ and $N_{\max}$ to the *Sending*UE. In the path discovery phase, similar to DSR [11], the *Sending*UE broadcasts an RREQ through the ith path to Node B to collect $P_{\mathrm{total},i}$. In this phase, each *Backer*UE floods the RREQ with transmission power $P_{\mathrm{TX\_RDP}}$ and discards the RREQ that exceeds the hop count limitation $N_{\max}$. Based on the collected $P_{\mathrm{total},i}$, Node B can identify the minimum-power path. As an option, Node B may refuse the ODMA request if $\min_i P_{\mathrm{total},i} \gg P_{\mathrm{opt}}$. In the "path setup phase," Node B sends an RREP packet along the identified path to configure the *Relay*UEs.

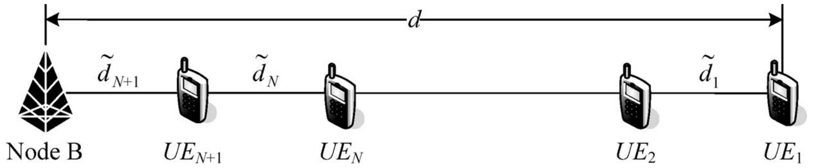

Fig. 1. Colinear network topology consisting of $N+2$ colinear nodes, $UE_1, \ldots, UE_{N+1}$, and Node B.

Note that the proposed PER differs from DSR in the following respects. First, PER can predict P_{opt} before the route discovery. Second, the transmission power utilized to forward the RREQ is αP_{ref} in DSR but is $P_{\text{TX\_RDP}}$ in PER ($\alpha P_{\text{ref}} \gg P_{\text{TX\_RDP}}$). Third, the hop count limitation for RREQ is infinite in DSR but is $N_{\max}$ in PER. The derivations of $P_{\text{TX\_RDP}}$, $N_{\max}$, and P_{ini} are elucidated next.

We investigate P_{opt} by considering a colinear network topology as shown in Fig. 1, where Node B, N *Relay*UEs, and *Sending*UE (i.e., UE_1) are located along a line. For the sake of simplicity, *Relay*UEs are numbered in order and denoted as UE_j, where $j = 2, \ldots, N+1$. Let d be the distance between *Sending*UE and Node B. Assume that the UE density in a cell is sufficiently high such that a UE can be found at any location along the line. Let the continuous random number $\tilde{d}_j$ denote the distance between UE_j and UE_{j+1}. During ODMA communication, the UEs are operating in TX and RX modes. In TX mode, the transmission power required by a UE depends on the radio channel condition. Typically, the radio channel condition is characterized by a large-scale propagation model[1] and a small-scale propagation model[2] [14]. Rodoplu and Meng [8] have proven that a minimum-power network design is fundamentally the same as that which considers only the path loss. Hence, only a path loss propagation model was considered in the analysis and simulation. The path loss model with the following parameters is used herein: a power law attenuation factor n $(4 \geq n \geq 2)$, antenna gain of a UE's transmitter (receiver) G_t (G_r), the wavelength of the modulated signal λ, the system loss factor L $(L \geq 1)$ [14], and the power required by the UE to correctly decode a message P_d. Note that P_d could be properly set by considering the effects of shadowing and fast fading in the implementation. With the characteristics, we have the following lemma.

Lemma 1: The total power (P_{opt}) and the number of *Relay*UEs (N_{opt}) required in the optimal ODMA path are shown in (1) and (2), respectively, at the bottom of the page. In (1) and (2), $k = ((4\pi)^2 L / G_t G_r \lambda^2) P_d$.

Proof: Denote $P_{\text{TX},j}$ and $P_{\text{RX},j}$ as the powers of UE_j in TX mode (where $\alpha P_{\text{ref}} \geq P_{\text{TX},j} \geq P_{\text{ref}}$) and RX mode (where $P_{\text{RX},j} = \beta P_{\text{ref}}$), respectively. The power transmitted by UE_j and received by UE_{j+1}, denoted as $P_{r,j+1}(\tilde{d}_j)$, is obtained by applying the Friis free space equation [14]

$$P_{r,j+1}(\tilde{d}_j) = \frac{P_{\text{TX},j} G_t G_r \lambda^2}{(4\pi)^2 \tilde{d}_j^n L} \triangleq \frac{1}{k_0} P_{\text{TX},j} \tilde{d}_j^{-n} \tag{3}$$

where $k_0 = (4\pi)^2 L / G_t G_r \lambda^2$. For successful reception, $P_{r,j+1}(\tilde{d}_j)$ should not be less than P_d. Hence

$$P_{\text{TX},j} = k_0 \tilde{d}_j^n P_{r,j+1}(\tilde{d}_j) \geq k_0 \tilde{d}_j^n P_d \triangleq k \tilde{d}_j^n \tag{4}$$

where $k = k_0 P_d$. The variable $P_{\text{total},i}$ is obtained by summing the power required by all transmitters and receivers of the *Sending*UE and *Relay*UEs. That is,

$$\begin{aligned} P_{\text{total},i} &= \sum_{j=1}^{N+1} P_{\text{TX},j} + \sum_{j=2}^{N+1} P_{\text{RX},j} \\ &= \begin{cases} \sum\limits_{j=1}^{N+1} k\tilde{d}_j^n + N\beta P_{\text{ref}}, & \text{for } k\tilde{d}_j^n > P_{\text{ref}} \\ (N+1)P_{\text{ref}} + N\beta P_{\text{ref}}, & \text{for } P_{\text{ref}} \geq k\tilde{d}_j^n. \end{cases} \end{aligned} \tag{5}$$

First, we consider the case that $P_{\text{TX},j} > P_{\text{ref}}$, that is,

$$\tilde{d}_j > \sqrt{[n]}\frac{P_{\text{ref}}}{k}. \tag{6}$$

By taking the expectation on both sides of (6) and replacing $E[\tilde{d}_j]$ with $d/(N+1)$, we obtain

$$d\sqrt[n]{\frac{k}{P_{\text{ref}}}} - 1 > N \geq 0. \tag{7}$$

$$P_{\text{opt}} = \min_i P_{\text{total},i}\big|_{N=N_{\text{opt}}} = \begin{cases} k\frac{d^n}{(N_{\text{opt}}+1)^{n-1}} + N_{\text{opt}}\beta P_{\text{ref}}, & \text{for } 0 < N_{\text{opt}} < \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1 \\ (N_{\text{opt}} + 1 + N_{\text{opt}}\beta)P_{\text{ref}}, & \text{for } N_{\text{opt}} \geq \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1 \end{cases} \tag{1}$$

$$N_{\text{opt}} = \begin{cases} \left\lfloor \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1, \right\rfloor, & \text{if } \left(\left\lceil \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1\right\rceil + \beta\right) P_{\text{ref}} > \frac{kd^n}{\left\lfloor \sqrt[n]{\frac{k}{P_{\text{ref}}}}d \right\rfloor^{n-1}} \\ \left\lceil \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1\right\rceil, & \text{otherwise} \end{cases} \tag{2}$$

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[1] A large-scale propagation model is utilized to predict the mean signal power for a relatively long transmitter–receiver separation. The path loss and the shadowing effect are considered.

[2] Small-scale propagation model characterizing the rapid fluctuations of the received signal strength over a very short distance. Delay spread due to multipath and Doppler effects is considered.

From (5), $P_{\text{total},i}$ is derived by

$$P_{\text{total},i} = k\left(\sum_{j=1}^{N}\tilde{d}_j^n + \left(d - \sum_{j=1}^{N}\tilde{d}_j\right)^n\right) + N\beta P_{\text{ref}} \quad \text{for} \quad d\sqrt[n]{\frac{k}{P_{\text{ref}}}} - 1 > N \geq 0. \tag{8}$$

The lower bound of (8) is obtained by varying $\tilde{d}_j$, that is,

$$\min_i P_{\text{total},i} = P_{\text{total},i}|_{\tilde{d}_j = \bar{d}_j}, \quad \text{for } {}_{j=1,\ldots,N+1}. \tag{9}$$

The optimal distance between adjacent nodes $\bar{d}_j$ that results in the minimum $P_{\text{total},i}$ is obtained by $(\partial/\partial\tilde{d}_j)P_{\text{total},i} = 0$, for $j = 1, \ldots, N+1$. Thus

$$\bar{d}_1 = \bar{d}_2 = \cdots = \bar{d}_{N+1} = d - \sum_{i=1}^{N}\bar{d}_i = \frac{d}{N+1}. \tag{10}$$

Equation (10) demonstrates that, for a given N, the lower bound is achieved if the distances between any two adjacent *Relay*UEs are equal. Under this condition, the transmission power required by each *Relay*UE to reach its neighboring *Relay*UE is a constant, which is denoted as P_0, where

$$P_0 = k\tilde{d}_i^n|_{\tilde{d}_i = \bar{d}_i} = k\left(\frac{d}{N+1}\right)^n. \tag{11}$$

From (8) and (11), $\min_i P_{\text{total},i}$ is obtained by

$$\begin{aligned}\min_i P_{\text{total},i} &= (N+1)P_0 + N\beta P_{\text{ref}} \\ &= \left(k\frac{d^n}{(N+1)^{n-1}} + N\beta P_{\text{ref}}\right) \\ &\quad \text{for} \quad 0 < N < \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1.\end{aligned} \tag{12}$$

Equation (12) is a monotonically decreasing function of N because $(d/dN)P_t < 0$, for $n \geq 2$ and $N < \sqrt[n]{(k/P_{\text{ref}})}d - 1$. Since N should be an integer, P_{opt} is obtained when

$$N = N_{\text{opt}} = \left\lfloor \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1 \right\rfloor. \tag{13}$$

Now consider the case that $P_{\text{TX},j} \leq P_{\text{ref}}$, or equivalently, $N \geq \sqrt[n]{k/P_{\text{ref}}}d - 1$. From (5), $\min_i P_{\text{total},i}$ is obtained by

$$\min_i P_{\text{total},i} = (N+1+N\beta)P_{\text{ref}} \quad \text{for} \quad N \geq \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1. \tag{14}$$

Equation (14) is a monotonically increasing function of N. Since N should be an integer, P_{opt} is located when

$$N = N_{\text{opt}} = \left\lceil \sqrt[n]{\frac{k}{P_{\text{ref}}}}d - 1 \right\rceil. \tag{15}$$

Combining (13) and (15), we obtain (2). And, P_{opt} given in (1) is obtained by combining (12) and (14). ■

A similar result of Lemma 1 has been obtained in [15]. Lemma 1 indicates that P_t and P_{opt} depend on following parameters: UE capabilities (i.e., β, P_{ref}, P_d), the path loss exponent (i.e., n), the distance between a source UE and Node B (i.e., d), and the number of *Relay*UEs (i.e., N). Among these parameters, the only unknown factor is d. In mobile cellular networks, UE normally utilizes an open-loop power control mechanism [14] to estimate d. Let P_{BCH} and P_{avg} be the broadcast channel (BCH) power transmitted by Node B and the average power received by *Sending*UE, respectively. In UMTS, P_{BCH} is a constant and is periodically broadcasted by Node B. Hence, *Sending*UE can estimate d from (4), that is,

$$d = \sqrt[n]{\frac{P_{\text{BCH}}}{kP_{\text{avg}}}}. \tag{16}$$

From (4) and (16), the initial transmission power used by *Sending*UE to send the ODMA service request to Node B P_{ini} is given by

$$P_{\text{ini}} = kd^n = \frac{P_{\text{BCH}}}{P_{\text{avg}}}. \tag{17}$$

Lemma 1: suggests that, with $N_{\max} = N_{\text{opt}} + 1$ and $P_{\text{TX\_RDP}} = P_0 = k(d/N_{\max})^n$, an optimal path in a colinear network topology is obtained given sufficiently high UE density. For a cellular network with low UE density, the optimal path may not be found. To solve this problem, *Relay*UE must increase $P_{\text{TX\_RDP}}$ to find another *Relay*UE in its neighborhood. Therefore, the minimum-power path can still be obtained if $P_{\text{TX\_RDP}} = \delta P_0$ (i.e., $\alpha P_{\text{ref}}/P_0 \geq \delta \geq 1$) is applied. Note that, under this condition, the total power required by the minimum-power path is not less than P_{opt}.

Normally, *Relay*UEs are located between *Sending*UE and Node B. As demonstrated in Fig. 2, *Backer*UEs in the region where the two circles overlap (both solid circles centered at Node B and *Sending*UE have the same radius P_{ini}) could be possible *Relay*UE candidates. Hence, in PER, only these *Backer*UEs, rather than all *Backer*UEs in the entire cell, should forward RREQ during route discovery. These *Backer*UEs can be identified easily because they can receive both the ODMA service request and the confirmation from *Sending*UE and Node B, respectively.

Figs. 2 and 3 show a general network topology and the message flows employed to demonstrate a scenario of the PER mechanism, respectively. In this scenario, UE_1 is the *Sending*UE, UE_js, for $j = 2, \ldots, 12$, are *Backer*UEs, and $N_{\text{opt}} = 1$ is assumed. As shown in Fig. 2, UE_{11} cannot receive the ODMA service request from UE_1, and UE_{12} cannot receive the confirmation from Node B; hence, UE_{11} and UE_{12} automatically enter the SLP mode after timeout. The RREQ message traversing along UE_1–UE_6–UE_7 is discarded by UE_7 because $N_{\max}$ is reached. Not otherwise specified, messages are carried through the logical channels specified in parenthesis in Fig. 3 (i.e., ORACH denotes the ODMA random access channel [2]). The three phases of the PER mechanism are described as follows.

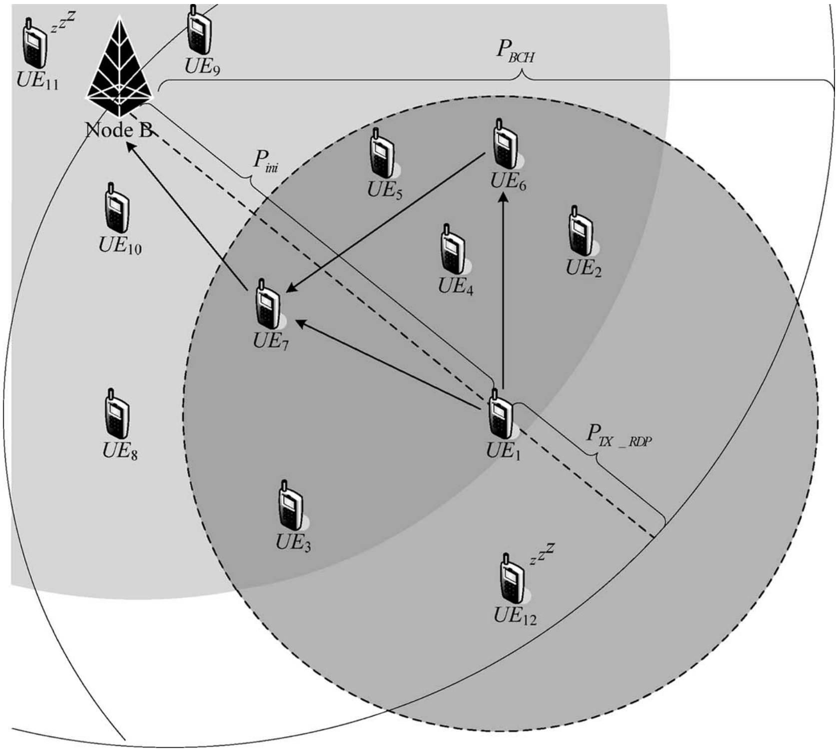

Fig. 2. Network topology illustrating the PER mechanism.

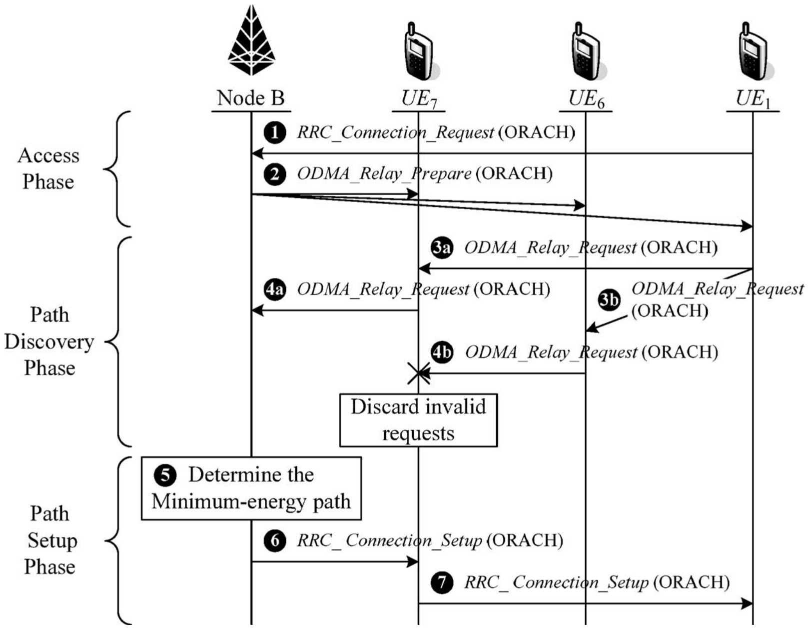

Fig. 3. Message flow of the PER mechanism.

A. *Access Phase*

Step 1) Prior to communicating with Node B, the *Sending*UE UE_1 measures P_{avg}, adjusts its transmission power to P_{ini}, and then sends RRC_Connection_Req [2] carrying P_{ini} to Node B.

Step 2) Upon receiving the RRC_Connection_Req message, Node B rejects the request if the request is nonattainable. Otherwise, Node B derives $P_{\mathrm{TX\_RDP}}$ and $N_{\max}$, adjusts its transmission power to P_{ini}, and acknowledges ODMA_Relay_Prepare carrying $P_{\mathrm{TX\_RDP}}$ and $N_{\max}$ to UE_1.

B. *Path Discovery Phase*

In the path discovery phase, the *Sending*UE adjusts its transmission power to $P_{\mathrm{TX\_RDP}}$ and floods an RREQ (i.e.,

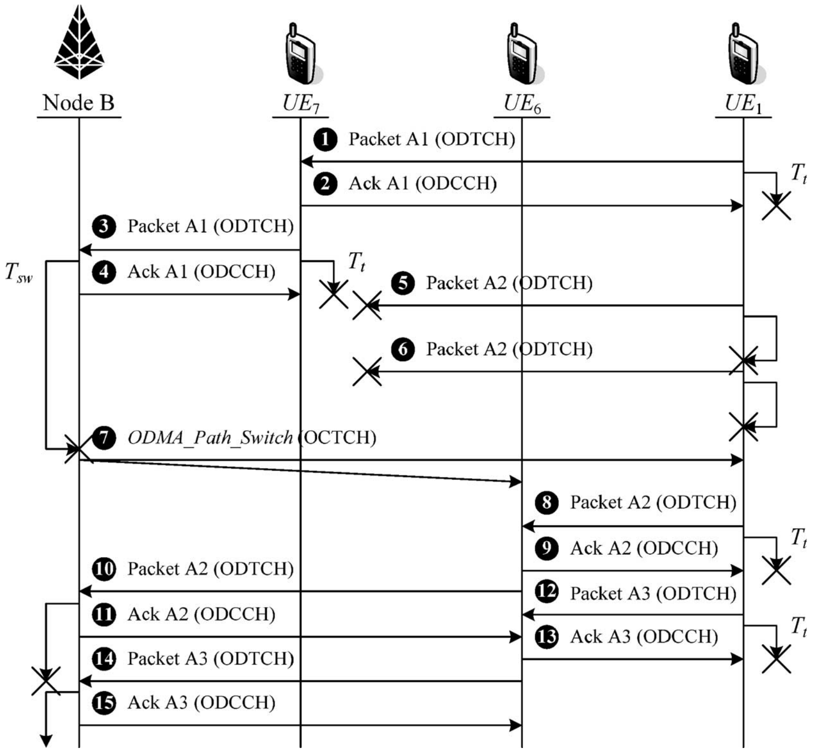

Fig. 4. Message flow of the PER mechanism link management functions.

ODMA_Relay_Req) the surrounding *Backer*UEs. The RREQ carries three parameters: namely 1) *SID*; 2) *RoutingList*; and 3) $P_{\mathrm{acc},j}$. The *SID* is the ODMA_ID of the *Sending*UE and is utilized to identify a specific ODMA connection request; the *RoutingList* contains ODMA_IDs of UEs that comprise the specific path; and the $P_{\mathrm{acc},j}$ is the accumulated power required for the path from *Sending*UE to UE_j.

Step 3a) UE_1 sends ODMA_Relay_Req carrying ($SID = 1$, $RoutingList =$ NULL, $P_{\mathrm{acc},1} = 0$) to its neighboring UEs, and UE_7 updates the accumulated power by

$$\begin{aligned} P_{\mathrm{acc},7} &= P_{\mathrm{acc},1} + P_{\mathrm{TX},1} + P_{\mathrm{RX},7} \\ &= P_{\mathrm{acc},1} + \max(P_{\mathrm{TX\_RDP}} - P_{r,7}, P_{\mathrm{ref}}) + \beta P_{\mathrm{ref}} \quad (18) \end{aligned}$$

where $P_{r,7}$ is the power of UE_1's ODMA_Relay_Req measured at UE_7.

Step 4a) UE_7 forwards the RREQ carrying ($SID = 1$, $RoutingList = 7$, $P_{\mathrm{acc},7}$) to Node B. Node B updates the total power $P_{\mathrm{total},i}$ of this first path by

$$\begin{aligned} P_{\mathrm{total},1} &= P_{\mathrm{acc},7} + P_{\mathrm{TX},7} \\ &= P_{\mathrm{acc},7} + \max(P_{\mathrm{TX\_RDP}} - P_{r,\mathrm{NodeB}}, P_{\mathrm{ref}}) \quad (19) \end{aligned}$$

where $P_{r,\mathrm{NodeB}}$ is the power of UE_7's ODMA_Relay_Req measured at Node B. Note that the power used by Node B's receiver is a common factor for all paths and thus is not considered in calculating $P_{\mathrm{total},i}$.

Step 3b) UE_6 receives the RREQ from UE_1, updates the triplet for this second path, and forwards the RREQ to UE_7.

Step 4b) UE_7 discards the RREQ because $N_{\max}$ is reached.

C. Path Setup Phase

Step 5) Node B determines the minimum-power path, which has the least $P_{\mathrm{total},i}$ among all discovered paths, and identifies UE_7 as the *Relay*UE from the *RoutingList*.

Step 6) Node B sends an RRC_Connection_Setup [2] to UE_7 carrying the ODMA traffic channel (ODTCH) and ODMA control channel (ODCCH) allocations [2]. The remaining *Backer*UEs whose ODMA_ID are not on the *RoutingList* move to the SLP mode.

Step 7) The ODMA communication path is established. The established communication path may be broken if mobility UEs are further considered. In such a mobile environment, Node B may repeat Steps 5) to 7) to create one or more backup communication paths to the *Sending*UE and enable link management functions for managing these paths. In the implementation, PER employs a well-known sliding-window scheme with a stop-and-wait automatic retransmission request (ARQ) mechanism to control data flow and retransmit error packets between adjacent *Relay*UEs. The same network topology shown in Fig. 2 is utilized to demonstrate a scenario of link management functions. In this scenario, UE_1–UE_7–NodeB is the primary path and UE_1–UE_6–NodeB is the backup path. Fig. 4 shows the message flow of the link management functions. In this scenario, the sliding-window size $W_{\max}$ is 2, and timers T_t and T_{sw} are required by UEs to control packet retransmission and by Node B to control path switching, respectively.

D. Flow Control and Error Control

Step 1) UE_1 starts its T_t and transmits packet A1 through the primary path to UE_7.
Step 2) UE_7 sends an acknowledgment to UE_1 denoting the successful reception of A1; then, UE_1 resets and stops its T_t.
Step 3) UE_7 starts its T_t and forwards A1 to Node B. Node B resets and starts T_{sw} whenever it correctly receives a new packet.
Step 4) UE_7 resets and stops its T_t after receiving the acknowledgment that A1 was received.
Step 5) UE_1 starts its T_t and transmits a packet A2 to UE_7. A2 is lost.
Step 6) UE_1 retransmits A2 after the expiry of its T_t. A2 is lost and T_t expires again. Since A2 has transmitted $W_{\max}$ times, the retransmission is stopped.

E. Switch to the Backup Path

Step 7) After T_{sw} expires, Node B switches to the backup path by sending ODMA_Path_Switch to UE_6 and UE_1 to activate the backup path.
Step 8) UE_1 starts its T_t and transmits the last unacknowledged packet A2 over the activated path to UE_6.
Step 9) UE_1 resets and stops T_t after receiving an acknowledgment from UE_6.
Step 10) UE_6 starts its T_t and forwards A2 to Node B; Node B resets and starts its T_{sw} after receiving a packet from UE_6.
Step 11) UE_6 resets and stops its T_t after receiving an acknowledgment from Node B.
Steps 12)–15) UE_1 successfully transmits A3 to Node B.

III. NUMERICAL RESULTS

Simulations were conducted to verify the effectiveness of the proposed PER mechanism. The load balancing capability of ODMA was not investigated herein. Hence, a single cell with 50–500 nonmobile UEs was considered. All UEs were assumed to be uniformly distributed within a hexagonal cell with radius 2500 m. The constants used herein are listed as follows: $\lambda = 15.78$ cm, $G_t = G_r = 1$, $L = 1$, $k_0 = 6334$, $\alpha = 20$, $\beta = 0.1, \ldots, 0.9$, $n = 2$, $P_{\text{ref}} = 20$ mW, $P_d = 10^{-8}$ mW, $d = 2100$ m, and $\delta = 2$. Each sample during the simulation was obtained by averaging the outcomes from 10^6 identical experiments. Both DSR and PER were simulated. The DSR was chosen as a benchmark because it can explore all paths and identify the minimum-power path in a cell. In the simulation, both DSR and PER found the same minimum-power path, but with different signaling overheads. Hence, the minimum-power path discovered by DSR was not specifically identified in Figs. 5 and 6. In Figs. 5 and 6, the analytical results are denoted with lines, while the simulation results are presented with symbols.

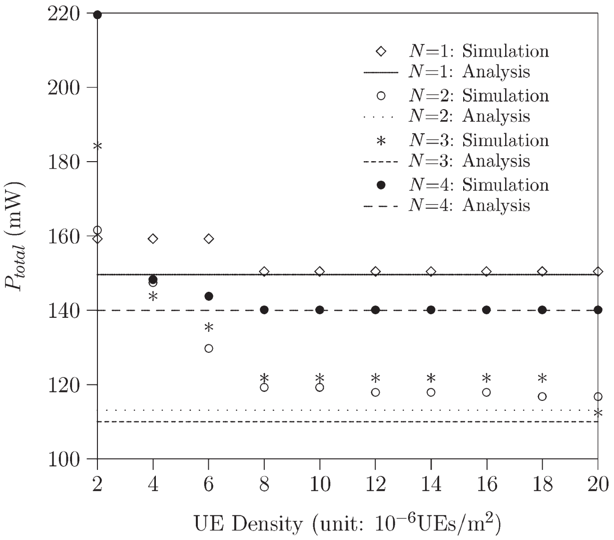

Fig. 5. Total power required by the path for various UE densities and N.

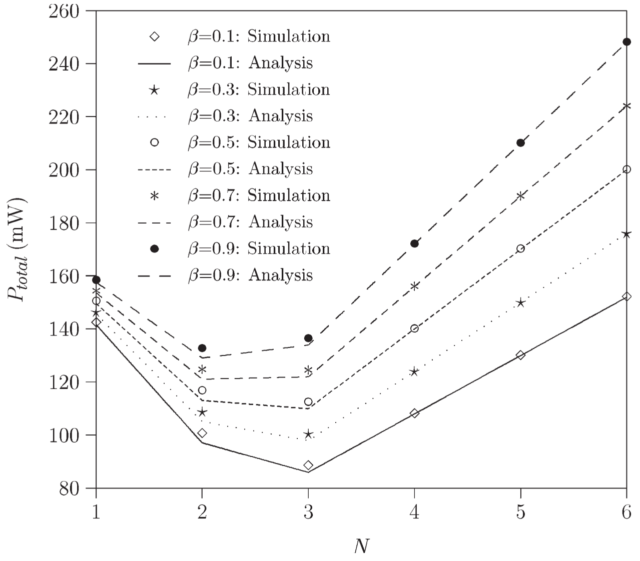

Fig. 6. Total power required by the path for various N and β.

The accuracy of the analysis was first verified by simulation. In Fig. 5, the total power required by the minimum-power path (i.e., P_{total}, where $P_{\text{total}} \simeq \min_i P_{\text{total},i}$) for various UE densities and the number of *Relay*UEs (i.e., N) were shown, in which $\beta = 0.5$ was assumed. Lemma 1 obtained $N_{\text{opt}} = 3$ and $P_{\text{opt}} = 110$ mW. Note that for $d = 2100$ m, *Sending*UE required 279 mW to transmit data directly to Node B without using ODMA. Simulation results showed estimation errors for low UE densities (Fig. 5). However, the estimation error was considerably reduced when the UE density was larger than 5×10^{-6} UEs/m^2. This finding was a result of the high UE density assumption in Lemma 1. For low UE density, *Relay*UEs

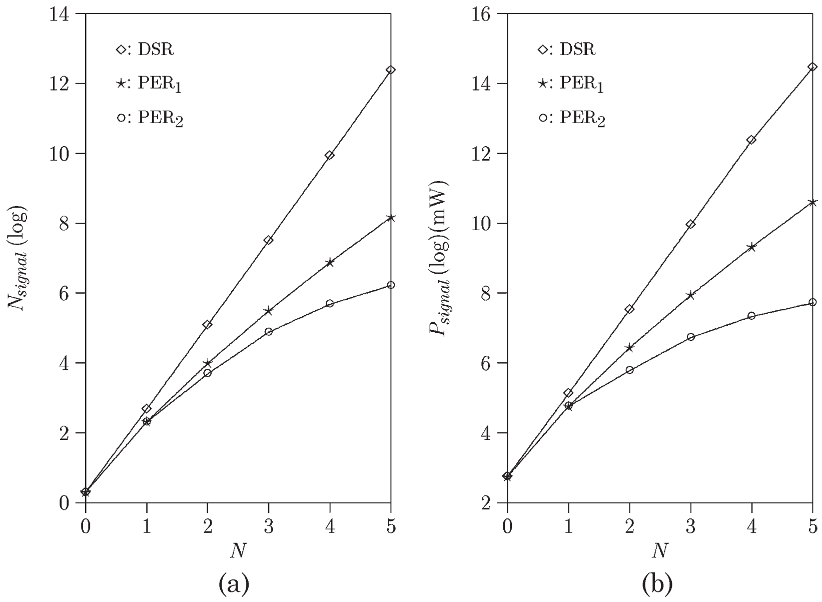

Fig. 7. Signaling cost of DSR and PER. (a) Total number of RREQ messages. (b) Total power consumed by RREQ messages.

could not be found at expected locations, and therefore, the lower bound was not achieved.

In the following two examples, the UE density is fixed to 2×10^{-5} UEs/m^2. Fig. 6 showed P_{total} for various Ns and βs. From Lemma 1, it can be derived that $N_{\text{opt}} = 2$ for $\beta = 0.7$ and $\beta = 0.9$, and $N_{\text{opt}} = 3$ for $\beta = 0.1$, $\beta = 0.3$, and $\beta = 0.5$; each derived N_{opt} coincided with the simulation results shown in Fig. 6. Fig. 6 demonstrated that for a fixed N, a decreased β resulted in a lowered P_{total} since a low power is required by the receiver of each *Relay*UE. For a given β, P_{total} was first decreased and then increased when N was increased from 1 to 6. The rationale for the variation of P_{total} is described as follows. Increasing N meant to add new *Relay*UEs in the path. Since these new *Relay*UEs consume extra power, it is not valuable to reduce P_{total} by increasing the number of *Relay*UEs unlimitedly, particularly for those *Relay*UEs that have high β. In other words, using *Relay*UEs closer than $1/(N_{\text{opt}} + 1)$ together results in greater overall power consumption since the savings in TX power from using smaller hops is lost given that nothing less than P_{ref} can be used. Lemma 1 proved that the minimum P_{total} was obtained if N_{opt} *Relay*UE was utilized in a path. For $N < N_{\text{opt}}$, increasing N implied a decrease in the distance between two adjacent *Relay*UEs; hence, the transmission power of existing *Relay*UEs was reduced. However, the cost was the extra power consumption introduced by new *Relay*UEs. In the region of $N < N_{\text{opt}}$, P_t was decreased because the power required by new *Relay*UEs is less than the power reduced by existing *Relay*UEs. However, in the region of $N > N_{\text{opt}}$, reducing the distance between two adjacent *Relay*UEs did not further reduce the transmission power of each *Relay*UE because the transmission power was bounded by P_{ref}; therefore, P_{total} was monotonically increased.

As mentioned earlier, both DSR and PER were able to locate the same minimum-power path; however, their signal costs were substantially different. In DSR, the UEs flood the RREQ over the entire cell with transmission power αP_{ref}. However, in PER, only selected *Backer*UEs flood the RREQ with transmission power δP_0. Fig. 7 shows the signaling cost of DSR and PER. The number of RREQs, (i.e., denoted as N_{signal}) and the total power consumed by the RREQs (i.e., denoted as P_{signal}) were investigated and illustrated in Fig. 7(a) and (b), respectively. In this example, $\beta = 0.5$, and $\delta = \alpha P_{\text{ref}}/P_0$ and $\delta = 2$ were used in PER$_1$ and PER$_2$, respectively. That is, both PER$_1$ and DSR used UE's maximum transmission power to flood the RREQ. As shown in the figures, the proposed PER mechanism dramatically reduced N_{signal} and P_{signal} because, in PER, fewer *Backer*UEs were allowed to forward the RREQ. The figures also demonstrated that a small δ results in a small N_{signal} and P_{signal}. However, reducing N_{signal} by lowering δ increased the risk of locating no path during the route discovery, particularly for those networks with low UE density. Since the optimization of δ is not essential for the effectiveness of the PER mechanism, its optimization will be the subject of future work.

IV. CONCLUSION

This paper presents a PER mechanism for ODMA cellular networks. In contrast to previous routing approaches, the proposed PER mechanism can estimate the power consumption of, and the number of relay nodes for, an optimal path without information from the other nodes. With the estimation, route discovery procedures originating from nonattainable ODMA requests can be prevented. The PER mechanism further provides attainable ODMA requests, a method to set the transmission power and maximum hop count to reduce the power consumption of each UE during the route discovery. The effectiveness of the proposed method is shown both theoretically and via simulation. Simulation results demonstrate that, with carefully chosen parameters, the PER mechanism can identify the minimum-power path with relatively low signaling cost compared to that of DSR.

TABLE I
PARAMETER DEFINITION

Parameters	Descriptions
N	Number of *RelayUE* in the collinear model
P_d	The power required by the UE to correctly decode a message
d	Distance between the *SendingUE* and Node B
$P_{TX,j}$	Transmission power of UE_j in TX mode, $\alpha P_{ref} \geq P_{TX,j} \geq P_{ref}$
$P_{RX,j}$	Receiving power of UE_j in RX mode, $P_{RX,j} = \beta P_{ref}$
$P_{r,j+1}(\tilde{d}_j)$	The power transmitted by UE_j and received by UE_{j+1}
n	The power-law attenuation factor
G_t	The antenna gain of an UE's transmitter
G_r	The antenna gain of an UE's receiver
L	The system-loss factor ($L \geq 1$)
λ	Wavelength of the modulated signal

APPENDIX

The definition of parameters involved in the analysis is summarized in Table I.

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