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Power-Efficient Routing (PER) Mechanism for ODMA Systems

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Abstract

This work presents a power-efficient routing (PER) mechanism to identify a minimum-power path for the Opportunity Driven Multiple Access (ODMA) communication in UMTS system. Prior to the route discovery, the PER mechanism utilizes an analytical solution to predict the total power and number of intermediate UEs required in the minimum-power path. With the prediction, the PER mechanism provides a method to set the transmission power and maximum hop-count such that the power consumption of each UE during the route discovery is significantly reduced. Simulation results demonstrate the accuracy of the prediction and the required signaling of PER is dramatically reduced compared to dynamic source routing (DSR).

1. Introduction

In a wireless communications system, the majority of transmission power is used to overcome radio propagation loss. To save power, it is beneficial to break a long path into a number of short links [1-3], and to relay data through these short links. In the Universal Mobile Telecommunications System (UMTS) [1], a cellular multi-hop method called Opportunity Driven Multiple Access (ODMA) has been proposed to reduce power required for transmission from mobile stations (also known as User Equipments (UEs) in UMTS), extend the coverage area of the base station (called Node B in UMTS), and increase the data transfer rate of users. User data in ODMA are exchanged between a sending UE and Node B by being relayed through intermediate UEs. Although there are advantages to ODMA, there are extra costs. The sending UE should establish a routing path through the intermediate UEs to Node B prior to data exchange. Moreover, each intermediate UE needs extra power to relay the data. Hence, the total power required for the ODMA communication depends on the way to identify intermediate UEs. Thus, power-efficient routing is a key issue for ODMA.

The functions of ODMA closely resemble those of mobile ad-hoc networks (MANET) [4]. However, they differ mainly in that Node B is located in a well-known fixed position in ODMA; however, both communication parties are mobile in MANET. Several power-aware routing methods [5-10] have been proposed for MANET and ODMA cellular networks. Most of the proposed methods are developed out of dynamic source routing (DSR) protocol [11] and 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 to 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 were first considered by Singh, Woo, and Mghavendra [5] in designing their routing method. Chang and Tassiulas [7] investigated the residual power of UEs in designing 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. In adopting directional antenna technology, each UE constructed a communication graph, removed the non-efficient edges from the graph, and derived a minimum-power routing topology. Vodafone Group [10] proposed an ODMA routing procedure in which the given local and end-to-end connectivity information was utilized to construct the routing path.

Two significant assumptions are made in these 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: each UE in a mobile cellular network does not have up-to-date information of other UEs due to the DRX[1] function. This assumption can be relieved by employing reactive-routing approaches [13]. However, existing reactive-routing approaches can only obtain the information of other UEs after executing route discovery; hence, some routing control messages are wasted on processing non-attainable ODMA requests (i.e., those requests whose power or latency requirements 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 the UE's maximum transmission power and without hop-count limitation. However, the UE's transmission power can be up to several Watts in a mobile cellular network and thus, cannot be neglected.

[1] With DRX, a UE is in sleep mode most of the time to save power and periodically wakes up to gather system information. The UE may not try to collect information from other UEs as all information would be obsolete after returning to sleep mode.

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This work presents a power-efficient routing (PER) mechanism to identify a minimum-power path for the ODMA communication. Different to existing reactive-routing approaches, the PER mechanism utilizes an analytical solution to predict the total power and number of intermediate UEs required in the minimum-power path prior to the route discovery. With the prediction, route discovery procedures originated from non-attainable 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 the setting, the power consumption of each UE during the route discovery is significantly reduced. The rest of this paper is organized as follows. The proposed PER mechanism is described in Section 2, and its key parameters and their effects on the system performance are discussed. Section 3 presents an investigation of the proposed PER mechanism's performance via numerical analysis and simulation. Conclusions are finally drawn in Section 4.

2. PER Mechanism

An ODMA network comprises a Node B and several ODMA-enabled UEs, which are identified by their user-specific identities (ODMA_IDs). To simplify this presentation, from this point forward the term UE will only denote an ODMA-enable UE. In an ODMA transmission, the role of UEs can be categorized as three types: *SendingUE*, *BackerUE*, and *RelayUE*. A *SendingUE* is the UE that originates the ODMA transmission. The other UEs that participate in the ODMA communication within the cell are known as *BackerUE*s. Among these *BackerUE*s, some will be identified as *RelayUE*s, which are responsible for relaying data packets between the *SendingUE* and Node B. Note that UEs that do not have sufficient residual-power may optionally disable some ODMA functionalities to minimize unnecessary power consumption.

Three power-consumption modes of the UE are considered herein: sleep (SLP), receiving (RX), and transmitting (TX). The UE consumes the least amount of power while in SLP mode, during which only a timer is activated. In RX mode, the receiver is turned on and thus, 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 to transmit data. Details of the PER mechanism are described as follows. Before going into details, the PER mechanism's parameters are defined.

- P_{ref} and αP_{ref} are the minimum and maximum power consumed by the UE in TX mode; 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; and, α, β, and γ are constants, where $\alpha > 1 >> \beta > \gamma > 0$ [2].
- P_{T_RDP} is the transmission power used by 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*, and N_{opt} is the number of *RelayUE*s required by an optimal path. Note that the optimal path is identified only under perfect conditions (i.e., it can find *RelayUE*s at any location within a cell).
- $P_{total,i}$ is the total power required by the i-th path discovered in the *path discovery phase*, and P_{opt} is the total power required by the optimal path. Note that $P_{total,i} \geq P_{opt}$.
- P_{ini} is the transmission power used by the *SendingUE* to send the ODMA service request.

The PER mechanism consists of three phases: *access phase*, *path discovery phase*, and *path setup phase*. In *access phase*, the *SendingUE* 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} from P_{ini}. By using these predicted P_{opt} and N_{opt}, Node B can check whether the ODMA request is attainable or not. For non-attainable ODMA requests, Node B simply terminates the PER procedure by replying the *SendingUE* with a rejection message. For attainable ODMA requests, Node B further derives P_{T_RDP} and N_{max}, and sends a confirmation message carrying P_{T_RDP} and N_{max} to the *SendingUE*. In *path discovery phase*, similar to DSR [11], the *SendingUE* broadcasts an RREQ through the i-th paths to the Node B to collect $P_{total,i}$. In this phase, each *BackerUE* floods the RREQ with transmission power P_{T_RDP} and discards the RREQ that exceeds the hop-count limitation N_{max}. Based on the collected $P_{total,i}$, Node B can identify the minimum-power path. As an optional, Node B may still refuse the ODMA request if $\min_i P_{total,i} >> P_{total}$. In *path setup phase*, Node B sends an RREP packet back to the *RelayUE*s along the identified path. The proposed PER differs from DSR in the following respects. First, PER can predict P_{opt} before the route discovery. Second, the hop-count limitation for RREQ is infinite in DSR but is N_{max} in PER. Third, the transmission power utilized to forward the RREQ is αP_{ref} in DSR but is P_{T_RDP} in PER. The derivation of P_{T_RDP}, N_{max}, and P_{ini} is next elucidated.

First investigate $P_{total,i}$ by considering a co-linear network topology (Fig. 1), in which Node B, N *RelayUE*s, and the *SendingUE* (i.e. UE_1) are located along a line. For sake of simplicity, *RelayUE*s are numbered in order and denoted as UE_j, where j=2,..., $N+1$. Let the distance between the *SendingUE* and Node B be d. Assume that the UE density in a cell is sufficiently high such that an UE can be found at any location along the line. The distance between UE_j and UE_{j-1} is a continuous random variable $\tilde{d}_j$. The UEs are operating in TX and RX modes during an ODMA communication. In TX mode, the transmission power required by an UE depends on the radio channel condition. Typically, the radio channel condition is characterized by a large-scale propagation model[2] and a small-scale propagation model[3] [14]. Rodoplu and Meng [8] proved that a minimum-power network design that addresses the increase in transmission power when handling large-scale variations is fundamentally the same design as that which considers only the path loss. Hence, a path-loss model with the following characteristics is employed: a power-law attenuation factor n [14]; antenna gain of an UE's transmitter (receiver) G_t (G_r); and, the system-loss factor L ($L \geq 1$). The following *Lemma* is first presented.

. For a given N, the lower bound of the power required by the path to Node B, denoted as P_t, is obtained by

$$P_t = \min_i P_{total,i} = \begin{cases} k\dfrac{d^n}{(N+1)^{n-1}} + N\beta P_{ref}, & \text{for } 0 < N < \sqrt[n]{\dfrac{k}{P_{ref}}}d - 1, \\ (N+1+N\beta)P_{ref}, & \text{for } N \geq \sqrt[n]{\dfrac{k}{P_{ref}}}d - 1, \end{cases}$$

where $k = \dfrac{(4\pi)^2 L}{G_t G_r \lambda^2} P_d$; λ is the wavelength, and P_d is the power required by the UE to correctly decode a message. Note that P_d can be properly set by considering effects of shadowing and fast fading. The total power required by the optimal path, denoted by P_{opt}, is attained when $N = N_{opt}$. That is, $P_{opt} = P_t|_{N=N_{opt}}$, where

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

Due to the space limitation, the derivation of Lemma 1 is not presented herein.

A similar result of *Lemma 1* is also obtained in [15]. *Lemma 1* proves that P_t and P_{opt} depends 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 the Node B (i.e., d); and, the number of *RelayUE*s (i.e., N). Among these parameters, the only unknown factor is d. In mobile cellular networks, the UE normally utilizes an open-loop power control mechanism [14] to estimate d. Let P_{BCH} and P_{avg} be the BCH power transmitted by Node B and the power received by the *SendingUE*, respectively. In UMTS, P_{BCH} is a constant and is periodically broadcasted by Node B. Hence, the *SendingUE* can estimate d based on the path loss model, that is,

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

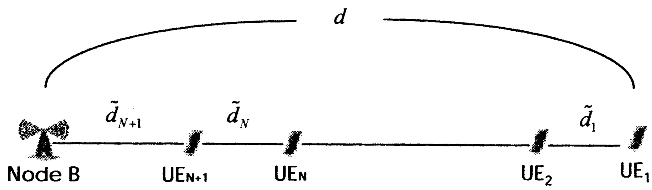


Figure 1. A co-linear network topology consisting of N+2 co-liner nodes, UE_1,..., UE_{N+1} and Node B.

Hence, the initial transmission power used by the *SendingUE* to send the ODMA service request to the Node B, P_{ini}, is given by

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

Lemma 1 suggests that, with $N_{max} = N_{opt} + 1$ and $P_{T\_RDP} = P_0$, an optimal path in a co-linear network topology is obtained given sufficiently high UE-density. For low UE-density, the optimal path may not be found. To solve this problem, a *RelayUE* can increase P_{T_RDP} and find another *RelayUE* in its neighborhood. Therefore, under a general condition where UEs density could be low and UEs are not located along a line, the minimum-power path can still be obtained if $N_{max} = N_{opt} + 1$ and $P_{T\_RDP} = \delta P_0$ (i.e., $\alpha P_{ref} / P_0 \geq \delta \geq 1$) is used. Note that, under this condition, the total power required by the minimum-power path is higher than P_{opt}.

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

Figures 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 *SendingUE*; UE_j, for j=2,...,12, are *BackerUE*s; and, $N_{opt} = 1$ is assumed. As shown in Fig. 2, UE_{11} cannot receive the ODMA service request from UE_1 and UE_{12}

[2] 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.

[3] Small-scale propagation model characterizes the rapid fluctuations of the received signal strength over a very short distance. Delay spread due to multi-path and Doppler effects are considered.

cannot receive the confirmation from Node B; hence, UE_{11} and UE_{12} automatically enter 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. Without otherwise specified, messages are carried through the logical channels specified in parenthesis in Fig. 3 (i.e., ORACH denotes the ODMA random access channel [1]). The three phases of the PER mechanism are described as follows.

Step 1. Prior to communicating with Node B, the *SendingUE* UE_1 measures P_{avg} , adjusts its transmission power to P_{ini} , and then sends an *RRC Connection Req* [1] carrying P_{ini} to Node B.

Step 2. Upon receiving the *RRC Connection Req* message, Node B adjusts its transmission power to P_{ini} and acknowledges an *ODMA Relay Prepare* carrying P_{T_RDP} and N_{max} to UE_1.

In the path discovery phase, the *SendingUE* adjusts its transmission power to P_{T_RDP} and floods an RREQ (i.e., *ODMA Relay Req*) to surrounding *BackerUE*s. The RREQ carries three parameters: *SID*, *RoutingList*, and $P_{acc,j}$. The *SID* is the ODMA_ID of the *SendingUE* utilized to identify a specific ODMA connection request; the *RoutingList* contains ODMA_IDs of UEs that comprise the specific path; and, the $P_{acc,j}$ is the accumulated power required for the path from *SendingUE* to UE_j.

Step 3a. UE_1 sends an *ODMA Relay Req* carrying (SID=1, *RoutingList*=NULL, $P_{acc,1}$=0) to its neighboring UEs and UE_7 updates the accumulated power by

$$P_{acc,7} = P_{acc,1} + P_{T,1} + P_{R,7}$$
$$= P_{acc,1} + \max(P_{T\_RDP} - P_{R,7}, P_{ref}) + \beta P_{ref}.$$

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

$$P_{acc,total} = P_{acc,7} + P_{T,7} = P_{acc,7} + \max(P_{T\_RDP} - P_{R,NodeB}, P_{ref}).$$

Note that the power used by Node B's receiver is not considered.

Step 3b. UE_6 receives the RREQ from UE_1, updates the triplet, and forwards the RREQ to UE_7.

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

Step 5. Node B determines the minimum-power path, which has the least $P_{acc,total}$ among all discovered paths, and identifies UE_7 as the *RelayUE* from the *RoutingList*.

Step 6. Node B sends an *RRC Connection Setup* [1] to UE_7 carrying the ODMA traffic channel (ODTCH) and ODMA control channel (ODCCH) allocation [1]. The remaining *BackerUE*s whose ODMA_ID are not on the *RoutingList* move to SLP mode.

Step 7. The ODMA communication path is established.

The established communication path may be broken by the movement of UEs. As an optional, Node B may repeat Steps 5 to 7 to create one or more backup communication paths for the *SendingUE*.

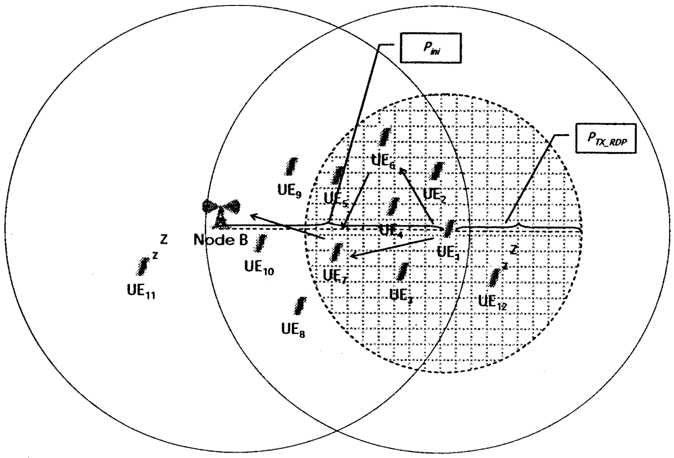


Figure 2. A network topology illustrates the PER mechanism.

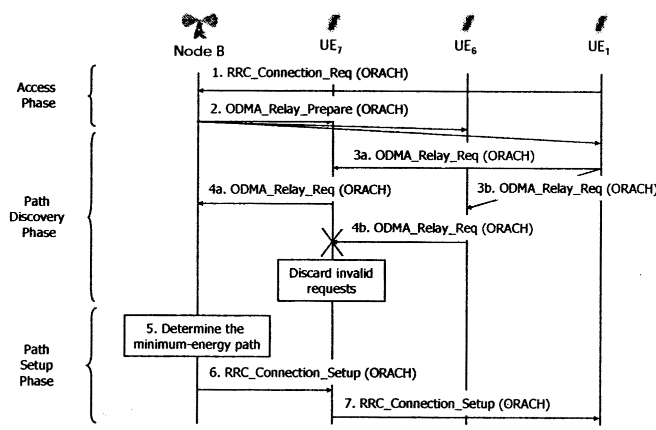


Figure 3. Message flow of the PER mechanism.

3. Numerical Results

Simulations were conducted to verify the effectiveness of the proposed PER mechanism. A discrete simulation model, which is similar to the one used in [16], was developed to validate the accuracy of the analysis. The load balancing capability of ODMA was not investigated herein. Hence, a single cell with 250 to 2,500 UEs was considered. All UEs were assumed to be uniformly distributed within a square area with dimensions 5km×5km. The constants used herein are listed as follows: f = 1900 MHz, $G_t = G_r = 1$, k_0= 6334, α = 20, β= 0.1,...,0.9, n = 2, P_{ref} = 20 mW, P_d = 10^{-8} mW, d = 2100 m, and δ = 1.5. 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 overhead. Hence, the optimum route discovered by DSR was not specifically identified in Figs. 4 and 5. In Figs. 4 and 5, numerical results are denoted with lines, while simulation results are presented with symbols.

The accuracy of the analysis was first verified by simulation. In Fig. 4, the total power required by the path (i.e., P_t) for various UE densities and number of *RelayUEs* (i.e., N) were shown, in which β = 0.5 was assumed. *Lemma 1* obtained N_{opt} = 3 and P_{opt} = 100 mW. Note that for d = 2100 m, the *SendingUE* required 279 mW to transmit data directly to Node B without using ODMA. Simulation results showed estimation errors for low UE-densities (Fig. 4). However, the estimation error was considerably reduced when UE-density was larger than 5×10^{-5} UEs/m^2. This finding was a result of the high UE-density assumption in *Lemma 1*. For low UE-density, the *RelayUEs* could not be found at expected locations and, therefore, the lower bound was not achieved.

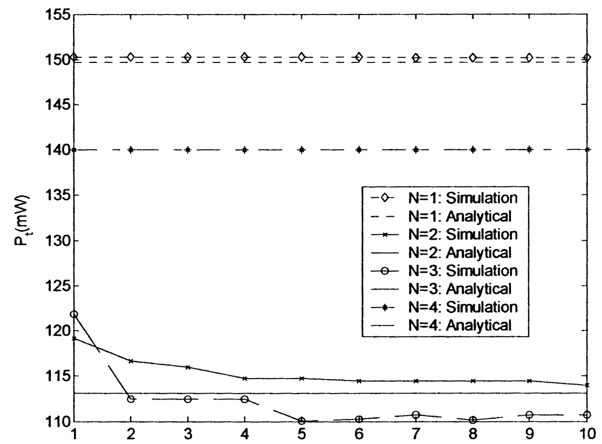


Figure 4. Total power required by the path for various UE densities and *N*.

In the following two examples, UE density is fixed to 5×10^{-5} UEs/m^2. Figure 5 showed the P_t for various N and β. From *Lemma 1*, it can be derived that $N_{opt} = 2$ for $\beta = 0.7$ and $\beta = 0.9$; and $N_{opt} = 3$ for $\beta = 0.1$, $\beta = 0.3$, and $\beta = 0.5$; each derived N_{opt} coincided with the simulation results shown in Fig. 5. Figure 5 demonstrated that for a fixed N, decreased β resulted in a lowered P_t since a low power is required by the receiver of each *RelayUE*. For a given β, P_t was first decreased and then increased when N was increased from 1 to 6. The rationale for the variation of P_t is described as follows. Increasing N meant to add new *RelayUEs* in the path. Since these new *RelayUEs* consume extra power, it is not valuable to reduce P_t by increasing the number of *RelayUEs* unlimitedly, particularly for those *RelayUEs* that have high β. In other words, using *RelayUEs* closer than $1/(N_{opt}+1)$ together results in greater overall energy use, 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_t was obtained if N_{opt} *RelayUEs* were utilized in a path. For $N < N_{opt}$, increasing N implied a decrease in the distance between two adjacent *RelayUEs*; hence, the transmission power of existing *RelayUEs* was reduced. However, the cost was the extra power consumption introduced by new *RelayUEs*. In the region of $N < N_{opt}$, P_t was decreased because the power required by new *RelayUEs* is less than the power reduced by existing *RelayUEs*. However, in the region of $N \geq N_{opt}$, reducing the distance between two adjacent *RelayUEs* did not further reduce the transmission power of each *RelayUE* because the transmission power was bounded by P_{ref}; therefore, P_t was monotonically increased.

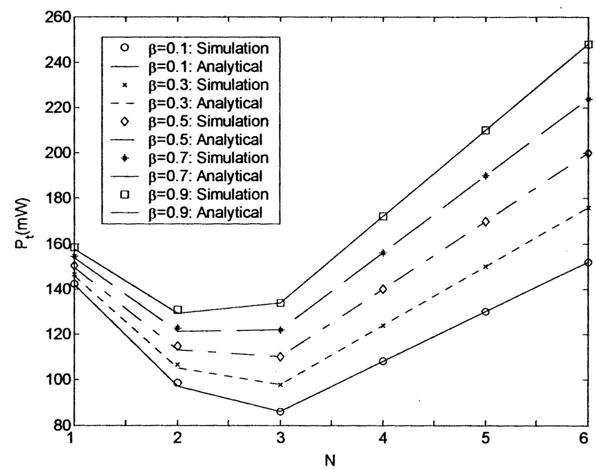
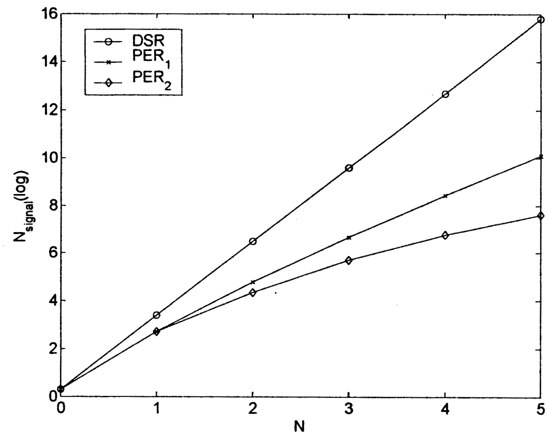


Figure 5. Total power required by the path for various *N* and β.

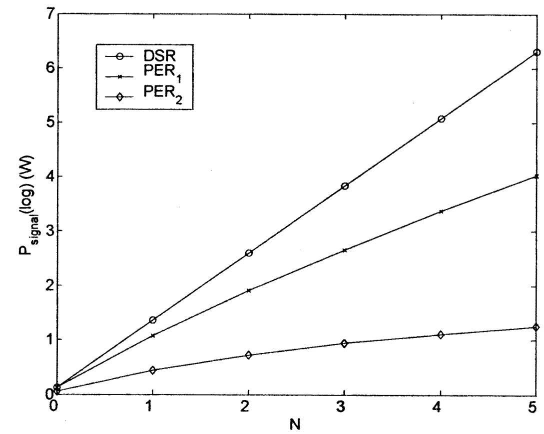
As mentioned earlier, both DSR and PER were able to locate the same minimum-power path; however, their signal costs were substantially different. In DSR, the UEs floods the RREQ over the entire cell with transmission power αP_{ref}. However, in PER, only selected *BackerUEs* flood the RREQ with transmission power δP_0. Figure 6 showed 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 were illustrated in Figs. 6(a) and 6(b), respectively. In this example, $\delta = \alpha P_{ref} / P_0$ and $\delta = 1.5$ were used in PER$_1$ and PER$_2$, respectively. The proposed PER mechanism dramatically reduced N_{signal} . For $\delta = \alpha P_{ref} / P_0$, the transmission power utilized by PER$_1$ was the same as that employed by DSR. However, N_{signal} of PER$_1$ was significantly reduced than that of DSR because, in PER, fewer *BackerUEs* were allowed to forward the RREQ. Simulation results of PER$_1$ and PER$_2$ also demonstrated that a small δ results in a small N_{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, it's optimization will be the subject of future work.

4. Conclusion

This work presents a PER mechanism for ODMA cellular networks. In contrast to previous routing approaches, the proposed PER mechanism accurately predicts the power consumption of, and the number of relay nodes for, an optimal path without information from the other nodes. Based on its prediction, Node B accepts the ODMA communication if the power and latency requirements of the requested UE are guaranteed. The effectiveness of the proposed mechanism 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.



(a) Total number of RREQ messages.



(b) Total power consumed by RREQ messages.

Figure 6. Signaling cost of DSR and PER.

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