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Publication Date
2010-03-01

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Ad Hoc Networks 8 (2010) 165–180

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Efficient broadcast for wireless ad hoc networks with a realistic physical layer

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ARTICLE INFO

Article history:
Received 31 December 2008
Received in revised form 15 May 2009
Accepted 18 June 2009
Available online 1 July 2009

Keywords:
Wireless ad hoc networks
Broadcast
Network coverage
Realistic physical layer

ABSTRACT

In this paper, we investigate the low coverage problem of efficient broadcast protocols in wireless ad hoc networks with realistic physical layer models. To minimize energy consumption, efficient protocols aim to select small set of forward nodes and minimum transmission radii. In ideal physical layer model, nodes within forward nodes' transmission ranges can definitely receive packets; therefore energy efficient protocols can guarantee full coverage for broadcasting. However, in networks with a realistic physical layer, nodes can only receive packets with probability. We present an analytical model to show that the transmission radii used for nodes can be used to establish a tradeoff between minimizing energy consumption and ensuring network coverage. We then propose a mechanism called *redundant radius*, which involves using two transmission radii, to form a buffer zone that guarantees the availability of logical links in the physical network, one for broadcast tree calculation and the other for actual data transmission. With this mechanism, we extend well-known centralized protocols, BIP and DBIP, and corresponding localized protocols, LBIP and LDBIP. The effectiveness of the proposed scheme in improving network coverage is validated analytically and by simulation.

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1. Introduction

Wireless ad hoc networks have emerged recently because of their potential applications in various situations such as battlefield, emergency rescue, and conference environments [1–4]. They are composed of possibly mobile devices such as sensors, laptop, or PDAs. Communications occur over a radio channel where the ranges are limited, and only close devices can communicate to each other. Therefore, devices must cooperate to complete tasks. In such network, broadcast is an indispensable operation needed for route discovery, information dissemination, publishing services, data gathering, task distribution, alarming, time synchronization, and so on. As devices rely on batteries with limited capacity, one of the most important criterion when designing communication protocols is energy efficiency.

The objective of efficient protocols is to minimize the total energy consumption for a broadcast task. Tree-based broadcasts provide the best energy efficiency since they try to select as small as possible forward nodes. Since energy consumption depends on transmission ranges, a straightforward way is to use radius as small as possible, normally right the distance between the forward node and its farthest relay node (shown in Fig. 1). This observation has been explored and applied in most previously proposed efficient protocols. However, their schemes are based on a common foundational assumption of an ideal physical layer model in which nodes within transmission range can definitely receive packets. However, it is not realistic in most practical situations. In reality the received power levels may show significant variations around the area mean power so that nodes can only receive packets with probabilities. In ad hoc networks with a realistic

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1570-8705/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.adhoc.2009.06.003

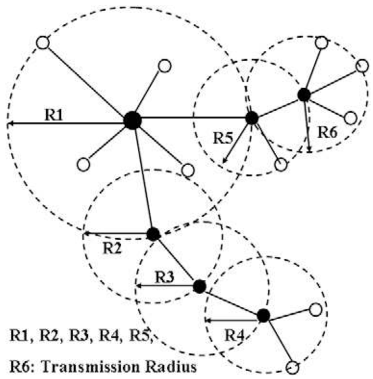

Fig. 1. An example of tree-based broadcast protocol under ideal physical layer model.

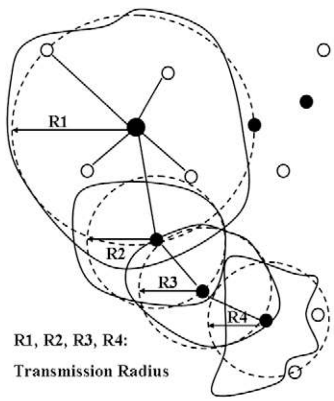

Fig. 2. Low coverage problem of tree-based efficient broadcast under a realistic physical layer.

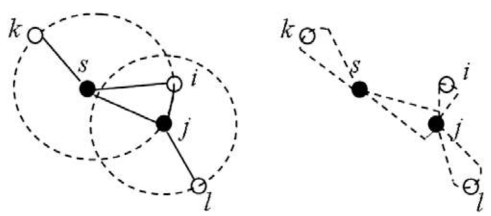

Fig. 3. The coverage redundancy comparison between omni and directional antennas.

physical layer, therefore, original tree-based efficient broadcast may suffer very low network coverage (shown in Fig. 2).

The low coverage problem of tree-based protocols is especially notable in networks with directional antennas compared to that with omni antennas, since directional antennas have less coverage redundancy. In Fig. 3 node *s* triggers one broadcast task and selects node *j* as its relay node. When node *s* and *j* apply omni antennas for emissions, node *i* is under the transmission range of both of them. However when they employ directional antennas and the beam width is narrowed, the overlapping on node *i* disappears. Since at this time node *i* has only one chance to receive a packet, the successful reception probability becomes smaller.

To address above low coverage problem, first, we set up mathematical models to evaluate the delivery ratio and energy consumption for one broadcast task under a realistic physical layer. Theoretical analysis reveals that the delivery ratio can be increased by lengthening forward nodes' transmission radius, however, the energy consumption will also increase. Hence, a tradeoff exists between increasing network coverage and minimizing energy consumption. We show how approximate radii can be computed and propose a general formula to derive transmission radii according to a required network coverage.

Next, we present our "redundant radius" scheme for efficient broadcasting protocols that makes use of above approximate radius calculation:

- First, after neighborhood information collection we employ smaller neighborhood range to calculate broadcast tree.
- Second, we apply longer radius as actual transmission radius which is based on derived approximate transmission radius to form a buffer zone that achieves the availability of logical links in the physical network.

We extend well-known centralized efficient protocols, BIP [5] and DBIP [6], and their corresponding localized protocols, LBIP [7] and LDBIP [8] by applying our "redundant radius" scheme. The effectiveness of the proposed scheme in achieving the required network coverage is confirmed via both performance analysis and simulation study.

The rest of this paper is organized as follows: In Section 2, we give a literature review of the related work and present the preliminaries and system model in Section 3. In Section 4, the computation of approximate transmission radii which balance the network coverage and energy consumption are considered, while in Section 5, we propose our "redundant radius" mechanism and extend four efficient broadcasting protocols that make use of derived target radius parameter. Then, Section 6 gives some experimental results and validates the effectiveness of the proposed scheme in improving network coverage. We finally conclude in Section 7.

2. Related work

2.1. Physical layer effect

Our work has been inspired by recent research work in [9–13]. Mineo Takai et al. [9] focused on the effects of physical layer modeling on the performance evaluation of higher layer protocols and has demonstrated the importance of the physical layer modeling even though the evaluated protocols do not directly interact with the physical layer. The set of relevant factors at the physical layer includes signal reception, path loss, fading, interference and noise computation, and preamble length.

Josh Broch et al. [10] targeted specially at the realistic ad hoc networking environment and extended the ns-2 network simulator to accurately model the link and physical layer behavior of the IEEE 802.11 wireless LAN standard, including a realistic wireless transmission channel model. They presented the performance comparison in packet-level among four multi-hop wireless ad hoc network routing protocols that cover a range of design choices: DSDV, TORA, DSR, and AODV.

Stojmenovic et al. [11–13] presented guidelines on how to design routing and broadcasting in ad hoc and sensor networks taking physical layer impact into consideration. They applied the log-normal shadow fading model to represent a realistic physical layer and derive the approximation for probability $p(d)$ of receiving a packet successfully as a function of distance d between two nodes. Since successful reception is a random variable related to distance d, they redefine the transmission radius r as the distance at which $p(r) = 0.5$. They proposed several localized routing schemes for the case when position of destination is known, optimizing expected hop count (for hop by hop acknowledgement), or maximizing the probability of delivery (when no acknowledgements are sent). They considered localized power aware routing schemes under realistic physical layer. Finally, they mentioned about the research for broadcasting in ad hoc network with realistic physical layer and proposed a concept of dominating sets to be used in broadcasting process.

2.2. Reliable broadcast protocols

There is another interesting research direction for broadcast protocol design, where although energy efficiency may also be taken into consideration, delivery ratio, i.e., network coverage is the main metric to consider. As energy efficient protocols aim to select minimum relay sets and radii which have minimum coverage redundancy, if a relay node assigned in constructed broadcast tree fails to receive a packet, it has few chance to receive the packet again which in turn causes the relay node fail to forward it to other areas.

Therefore, reliable protocols try to achieve good delivery ratio by keeping coverage redundancy in some level, but at the expense of a significant energy consumption. Basically, there are two types of reliable protocols [14]. One is node failure tolerance strategy where nodes are required to send back acknowledgements (ACKs) upon success receptions and if senders can not receive ACKs, retransmissions will be scheduled or a new broadcast tree could be calculated to choose alternative relay nodes [15,16]. Another scheme is to increase the number of relay nodes, i.e., increasing coverage areas. For example, Lou and Wu [17] proposed Double-Covered Broadcast (DCB) which selects relay nodes in such a way that not only every 2-hop neighbor node is covered, but also that all 1-hop neighbor nodes are covered by at least 2 forwarding nodes.

2.3. Broadcast oriented protocols

Among existing efficient protocols, broadcast oriented protocols consider the broadcast process from a given source node. Ingelrest et al. [18] investigated energy efficiency problem for LMST and RNG based broadcast oriented protocols and proposed optimal transmission radius for them. However, they did not extend their work into incremental power philosophy based protocols which are well-known for their energy conserving. Moreover, the crucial deficiency of their work is that they did not consider the impact of realistic physical layer such as log-normal shadowing model, and MAC layer such as IEEE 802.11.

2.3.1. Incremental power philosophy

A broadcast tree is computed from a source node by adding nodes one at a time. At each step, the less expensive action to add a node is selected, either by increasing the radius of an already transmitting node, or by creating a new emission from a passive one.

The classical example of incremental power philosophy is BIP proposed by Wieselthier et al. [5] which exploits the "wireless broadcast advantage" property, namely the capability for a node to reach several neighbors by using a transmission power level sufficient to reach the most distant one. BIP considers omni antennas, that is, a single transmission is received by all the neighboring nodes located within selected transmission range. At each step of the tree-construction process, a single node is added; variables involved in computing cost (and incremental cost) are transmitter powers. For adding a new node, we can only have two choices: set up a new emission to reach a new node or raise the length range of existing emission to check whether there is a new node covered or not. Fig. 4 shows a sample of BIP-based broadcast tree.

Directional Broadcast Incremental Power [6] (DBIP) algorithm is another good instance which applies the incremental power philosophy to network with directional antennas. In DBIP, at each step of the tree-construction, a single node is added, whereas variables involved in computing cost (and incremental cost) are not only transmitter power but beam width θ as well. That means for adding a new node, we can have more choices: set up a new directional antenna; raise the length range of beam; or enlarge the beam width. Experimental results show that DBIP has very good performance for energy saving.

However, both BIP and DBIP are centralized protocols in which changes in topology must be propagated throughout the network. Therefore, it is more ideal that each node can decide its own behavior based only on the information from nodes within a constant hop distance. Such distributed algorithms and protocols are called localized schemes [19–23].

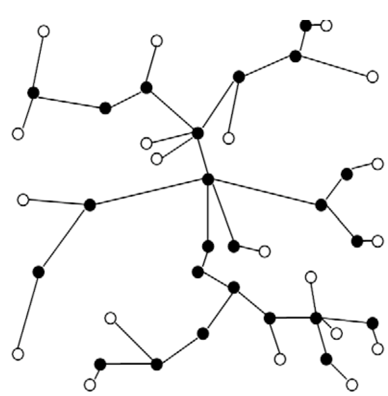

Fig. 4. A sample of BIP-based broadcast tree.

2.3.2. Localized schemes

For a node $v \in V$, the exact k-hop neighbor set, $H_k(v)$, is the set of nodes that is exactly k hops away from v and its k-hop neighbor set, $N_k(v) = \{v\} \cup H_1(v) \cup\ H_2(v) \cup, \ldots, \cup H_k(v)$, is the set of nodes that is at most k hops away from v. The k-hop location information of $v, L_k(v)$, is the location of its k-hop neighbor set, $N_k(v)$.

Each node extracts its own location information and builds its k-hop location information by exchanging $(k-1)$-hop location information with its neighbors via "Hello" messages. Therefore, k rounds of exchanges of the accumulative neighbor set between neighbors are needed to collect k-hop location information at node.

The source node s (the one that initiates the broadcast) computes the broadcast tree with its k-hop location information $L_k(s)$ and sends the broadcast packet B using new computed transmission range, while including $m-1$ hops computed relay information and the mth hop relay nodes' id in B. In addition, m can be different with k since during broadcast tree computing nodes will reset their actual transmission range rather than always applying constant maximum transmission range.

For any node u who receives B for the first time, three cases can happen:

- The packet contains both relay instructions for u and u's id. Node u will use these relay instructions to construct its own local broadcast tree. Then, instead of starting from an empty tree as s does, it extends the broadcast-tree based on what source s has calculated for it. By this way, the joint neighborhood nodes of s and u will use the same spanning tree.
- The packet contains only relay instructions for u. Node u will just follow these instructions to relay the packet.
- There are no relay instruction for u. In this case, node u does nothing.

By employing localized scheme to BIP, the Localized Broadcast Incremental Power (LBIP [7]) brings results really close to BIP which requires a global knowledge of the network to achieve close performance. Similarly, by applying localized scheme to DBIP, the Localized Directional Broadcast Incremental Power (LDBIP [8]) algorithm provides close performance to DBIP.

However, all the above broadcast schemes model networks as undirected graph $G = (V, E)$, where V is a set of nodes and E is a set of wireless links. A link exists between two nodes u and v if and only if their physical distance is less than a transmission range r. If we consider a realistic physical layer where link may not exist although their physical distance is less than radius, existing protocols should be redesigned.

3. Preliminaries and system models

3.1. Realistic physical layer

In wireless communication, basically the carrier wave propagates messages through the direct optical "line of sight" path between the radio transmitter and receiver. However, in the real world, multipath [24] occurs when there is more than one path available for radio signal propagation. The phenomenon of reflection, diffraction and scattering all give rise to additional radio propagation paths. Reflections occur from the surface of the earth and from buildings and walls. Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges). Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel.

Because of multipath effect, the actual received signal level is vector sum of all signals incident from any direction or angle of arrival. Some signals will aid the direct path, while other signals will subtract (or tend to vector cancel) from the direct signal path. Finally, the received power levels may show significant variations which cause success reception as statistic variable.

RF multipath problems can be mitigated in a number of ways: radio system design, antenna system design, signal or waveform design, building or environment design. However, multipath effect cannot be totally avoided.

Because of all kinds of physical layer factors, in reality the received power level may show significant variations around the area mean power [25]. Due to those variations, the coverage area will deviate from a perfect circular shape and consequently, some short links could disappear while long links could emerge (Fig. 5).

There are research directions where researchers aim to analyze realistic physical layer factors in detail and embed them into upper layer protocol design. However, there are three main considerations which prevent us working in that way. Firstly, realistic physical layer factors are too complicated to be modeled precisely and it is also not feasible to capture the dynamic variation caused by them, therefore up to now most researchers play with approximate mathematic models or make use of parameters to reflect the effects of those realistic physical layer factors. Secondly, according to different MAC protocols realistic physical layer effects can be also different. Thirdly, the OSI layered protocol design model divides communication work for each layer, therefore, employing complicated representation of realistic physical layer effects into the network layer design is not suitable and also not convenient. In a word, although realistic physical layer effects cannot be neglected, we still want to make use of some simple parameters to effectively represent their effects to facilitate network layer protocol design. Based on the

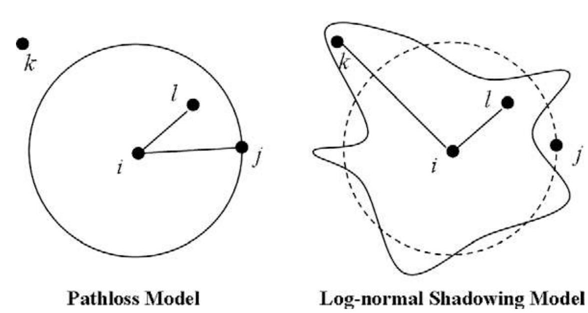

Fig. 5. Coverage comparison between ideal and realistic physical layer models.

guideline work of Stojmenovic et al. [11], we plan to use the parameter of packet reception success probability (p) to reflect the loss rate caused by reception power variation.

Since there are several realistic physical layer models and they have different properties, the packet success reception probability (p) under different physical layer models is also different. The exact computation of the packet reception probability p for use in routing and broadcasting decision is a time-consuming process and is based on several measurements (e.g. signal strengths, time delays, and GPS) which may cause some errors. It is therefore desirable to consider a reasonably accurate approximation that will be fast for use. In this paper we employ the widely used log-normal shadowing model [26], since Stojmenovic et al. [27–29] have derived the approximation of p for that model as a function of transmission radius r, reception distance d and packet length l.

3.2. MAC and link-layer model

As for link between nodes there exist two different operating models [28].

- End-to-End Retransmissions (EER): where the individual links do not provide link-layer retransmissions and error recovery.
- Hop-by-Hop Retransmissions (HHR): where each individual link provides reliable forwarding to the next hop using localized packet retransmissions (when retry limitation is reached, packets will be finally dropped).

Although HHR based MAC (Medium Access Control) protocols do increase the packet reception success probability, however, it is at the expense of retransmissions, i.e., energy consumption. Also the IEEE 802.11 MAC protocol, which is the emerging standard in wireless networks and widely used, performs HHR for routing. However, if a packet is broadcasted, neither acknowledgment nor retransmission is carried out. Considering that our goal is to let existing efficient broadcast protocols can still work well in realistic environment, in this paper we focus on EER model.

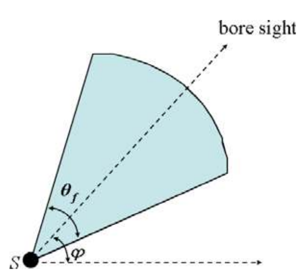

Fig. 6. Directional antenna propagation model.

3.3. Antenna model

We consider networks with not only omni antennas but also directional antennas. The use of directional antennas can permit energy savings and reduce interference by concentrating transmission energy where it is needed.

We use a directional antenna propagation model [29] as shown in Fig. 6 where the antenna orientation φ ($0 \leqslant \varphi < 2\pi$) of node is defined as the angle measured counter-clockwise from the horizontal axis to the antenna boresight and the antenna directionality is specified as the angle of beamwidth ($0 \leqslant \theta_f < 2\pi$). Table 1 shows the antenna classification based on the above model.

In this paper we focus on the modestly directional antenna which has the following characteristics:

- Beamwidth of each antenna cannot be adjusted, i.e., θ_f, is fixed for any node.
- Orientation of each antenna can be shifted to any desired direction to provide connectivity to a subset of the nodes that are within communication range.
- A single antenna beam is provided for each session in which a node participates.
- Each node knows the precise locations of its potential neighbors.

4. Analytical model

Our schemes are based on the observation that it is not always suitable to minimize the transmission radius because coverage issue has been brought forward under realistic physical layer. Large transmission radius is helpful to enhance coverage ratio, while it also causes large power consumption. Indeed, there exists a trade-off between achieving network coverage and maintaining energy efficiency. Table 2 shows notations used in this paper.

4.1. Energy consumption model

For the analysis convenience, we assume that all packets are of the same size (number of bits). Given that a packet is sent with transmission radius r and fixed beamwidth θ_f, the amount of energy expended to transmit it is a function of r and θ_f. Besides that, the transmitter also spends energy on signal processing which is independent of r and θ_f. For each neighbor node within its transmission coverage area, regardless of success reception, an overhead due to signal processing upon the reception behavior should also be taken into consideration and is also independent of r and θ_f. Without loss of generality, assume that there are n nodes within its transmission coverage area, the overall energy consumption for one transmission could be represented as

Table 1
Antenna classification.

	Omni directional	Modestly directional	Highly directional
Antenna Directionality	Fixed beamwidth	Fixed beamwidth	Variable beamwidth
Antenna Orientation	Unsteerable	Steerable	Steerable

Table 2
Notations used in this paper.

Notation	Description
β	Path loss
N	Total number of nodes in network
K	Number of forward nodes (plus source node)
d	Distance variable between two nodes
A	Network area
θ_f	Antenna beam width for any transmission session
D	Network density
r	Transmission radius variable for any forward node
$D(r)$	Transmission coverage (average neighbor number with r)
R_m	Maximum transmission range
C_r	Energy overhead due to reception signal processing
C_e	Energy overhead due to transmission signal processing
R_i	Transmission radius value for ith forward node
p	Packet reception probability variable function
P_i	Packet reception probability value for ith forward node
$\overline{P}$	Expected delivery ratio for one broadcast task
$\overline{E}$	Total expected energy consumption for one broadcast task

$$E(r) = ar^{\beta}\frac{\theta_f}{2\pi} + b + n \times c, \tag{1}$$

where β is path loss and basically $2 \leqslant \beta \leqslant 6$, and a, b and c are technology-dependent positive constants. Normally, the actual unit of energy consumption is Joules, however, by multiplying a corresponding factor, the value of $E(r)$ can be converted into any given units.

In above model, there are three coefficients to determine, and for the convenience of analysis and with an arbitrary unit, we obtain the equivalent form

$$E(r) = r^{\beta}\frac{\theta_f}{2\pi} + C_e + n \times C_r, \tag{2}$$

where C_e denotes energy consumption for transmission signal processing and C_r denotes overhead for packet reception; for omni antennas, i.e., $\theta_f = 2\pi$, the model can be simplified as

$$E(r) = r^{\beta} + C_e + n \times C_r. \tag{3}$$

Since C_e and C_r are determined by a large number of factors, such as length of packets, the ability of single processing and so on, the exact evaluation is quite challenging [24]. Under present-day technology, a reasonable approximation of them is derived for omni antenna emission by Rodoplu and Meng in their work [30], where when β is 4, C_e is approximated as 10^8 and C_r can be about $\frac{2}{3} \times 10^8$, i.e., $E(r) = r^4 + 10^8 + n \times \frac{2}{3} \times 10^8$. The previous work in [18] has proved that it is realistic and appropriate enough to be used as a reference for theoretical analysis.

4.2. Computation of suitable transmission radius

Let us consider a rectangular area A where N nodes are randomly placed. D is the network density defined as $D = N \times \frac{\pi R_m^2}{A} \times \frac{\theta_f}{2\pi}$ where R_m is the maximum transmission range and θ_f is the antenna beam. Assume in one broadcast task, source node emits one packet with a transmission radius R_1. There exist $K-1$ consecutive forward nodes and their neighbors' packet reception probability values are $P_1, P_2, \ldots, P_{K-1}$. P_K represents the packet reception probability value of last forward nodes' neighbors. If forward nodes cannot receive packets, there will be no more emission. Their own forwarding transmission radius values are $R_2, \ldots, R_K$, respectively. For any node with transmission radius r, we can calculate its transmission neighborhood density (average neighbors number), denoted by $D(r)$, as $D(r) = D \times \frac{\pi r^2 \times \frac{\theta_f}{2\pi}}{\pi R_m^2 \times \frac{\theta_f}{2\pi}} = \frac{Dr^2}{R_m^2}$.

On one hand, the total expected energy consumption, denoted as $\overline{E}$, will be

$$\begin{aligned}\overline{E} = {} & \left(R_1^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_1^2}{R_m^2}C_r\right) + P_1\left(R_2^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_2^2}{R_m^2}C_r\right) \\ & + P_1P_2\left(R_3^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_3^2}{R_m^2}C_r\right) + \cdots \\ & + P_1P_2,\ldots,P_{K-1}\left(R_K^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_K^2}{R_m^2}C_r\right) \\ = {} & \sum_{i=1}^{K}\left(\prod_{j=0}^{i-1}P_j\right)\left(R_i^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_i^2}{R_m^2}C_r\right),\end{aligned} \tag{4}$$

where $P_0 = 1$.

On the other hand, the expected delivery ratio, denoted as $\overline{P}$, is

$$\begin{aligned}\overline{P} & = \frac{P_1\frac{DR_1^2}{R_m^2} + P_1P_2\frac{DR_2^2}{R_m^2} + \cdots + P_1,\ldots,P_K\frac{DR_K^2}{R_m^2}}{N} \\ & = \frac{\sum_{i=1}^{K}\left(\prod_{j=1}^{i}P_j\right)\frac{DR_i^2}{R_m^2}}{N}.\end{aligned} \tag{5}$$

Because of coverage redundancy, (as illustrated in Fig. 7, node i with omni antennas is the neighbor of not only source node s, but also forward node j), nodes can receive a packet more than one time, therefore above calculation has unexpected error range. In broadcast task, forward nodes have critical roles in determining delivery ratio. Since in our assumption forward nodes are consecutive and dependent on each other to relay packets, we employ $P_1P_2,\ldots,P_{K-1}P_K = \prod_{i=1}^{K}P_i$ as our approximate expected delivery ratio for evaluation.

For the analysis convenience, let us consider one special node deployment as illustrated in Fig. 8, where transmission radius values and packet reception probability values of all forward nodes are the same, that is, $P_1 = P_2 = \cdots = P_K = P, R_1 = R_2 = \cdots = R_K = R$. However, the analysis conclusion based on this specific deployment is also suitable for that on random deployment which will be

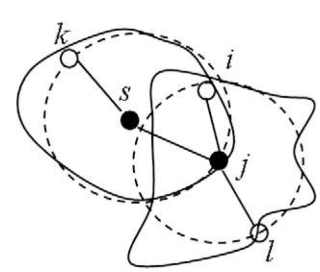

Fig. 7. An example of coverage redundancy.

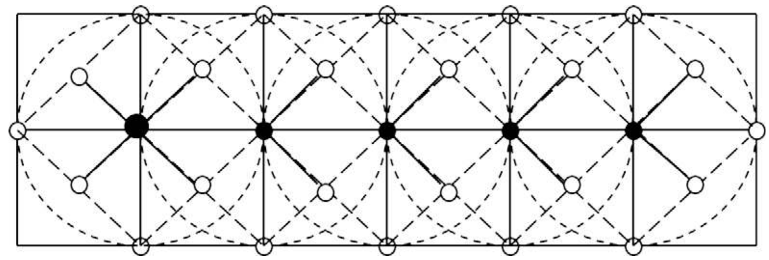

Fig. 8. An example of special node deployment.

shown in our simulation work. Given our specific deployment, the expected broadcast delivery ratio $\overline{P} = P^K$ and Eq. (4) can be rewritten as

$$\begin{aligned}\overline{E} &= \sum_{i=1}^{K}\left(\prod_{j=0}^{i-1} P_j\right)\left(R_i^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR_i^2}{R_m^2}C_r\right) \\ &= (1 + P + P^2 + \cdots + P^{K-1})\left(R^{\beta}\frac{\theta_f}{2\pi} + C_e + \frac{DR^2}{R_m^2}C_r\right) \\ &= \begin{cases}\frac{1-P^K}{1-P}\left(\frac{R^{\beta}\theta_f}{2\pi} + C_e + \frac{DR^2}{R_m^2}C_r\right) & P \neq 1 \\ K\left(\frac{R^{\beta}\theta_f}{2\pi} + C_e + \frac{DR^2}{R_m^2}C_r\right) & P = 1\end{cases} \\ &= \begin{cases}\frac{1-P^K}{1-P}\left(\frac{R^{\beta}\theta_f}{2\pi} + C_e + \frac{N\pi R^2 C_r}{A}\right) & P \neq 1 \\ K\left(\frac{R^{\beta}\theta_f}{2\pi} + C_e + \frac{N\pi R^2 C_r}{A}\right) & P = 1.\end{cases}\end{aligned} \quad (6)$$

When $P = 1$ which is the ideal case with ideal physical layer model, node will definitely receive packet successfully. When $P \neq 1$ which is the case with realistic physical layer, our goal is to maximize the approximate delivery ratio $\overline{P}$ and at the same time minimize the total expected energy consumption $\overline{E}$. That is

$$\begin{cases}\mathit{Maximize} & P^K, \\ \mathit{Minimize} & \frac{1-P^K}{1-P}\left(\frac{R^{\beta}\theta_f}{2\pi} + C_e + \frac{N\pi R^2 C_r}{A}\right),\end{cases}$$

where R is the certain value of transmission radius r and P is the value of packet reception probability p.

Stojmenovic et al. [27–29] derived the approximation for p for log-normal shadowing physical layer as a function of transmission radius r, reception distance d and packet length l which is shown in Eq. (7)

$$p = \begin{cases} 1 - \frac{\left(\frac{d}{r}\right)^{q\beta}}{2} & 0 \leqslant d < r, \\ \frac{\left(\frac{2r-d}{r}\right)^{q\beta}}{2} & r \leqslant d \leqslant 2r, \\ 0 & \mathit{others}, \end{cases} \quad (7)$$

where $q\beta$ is the power attenuation factor and q depends on l. They have also proved that when packet length l is 120 (bits) and path loss β ranges between 2 and 6 the error of this model with $q = 2$ can be restricted within 4%.

We employ the reference energy consumption model (where $\beta = 4, C_e = 10^8, C_r = \frac{2}{3} \times 10^8$ and $\theta_f = 2\pi$) presented in the previous section and the above packet reception probability model (where $q = 2$) for analysis. Without lose of generality, we assume that 29 nodes ($N = 29$) with 4

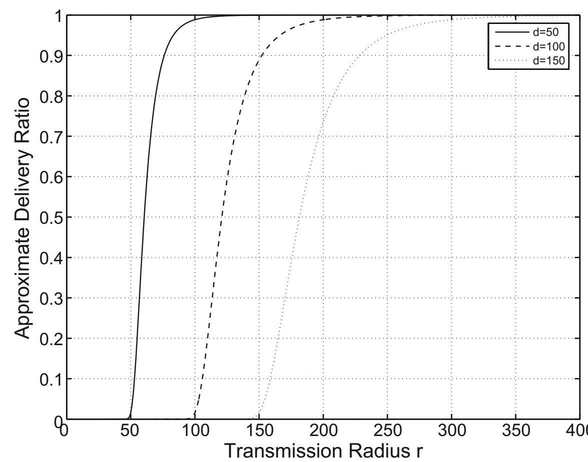

Fig. 9. A sample of approximate delivery ratio.

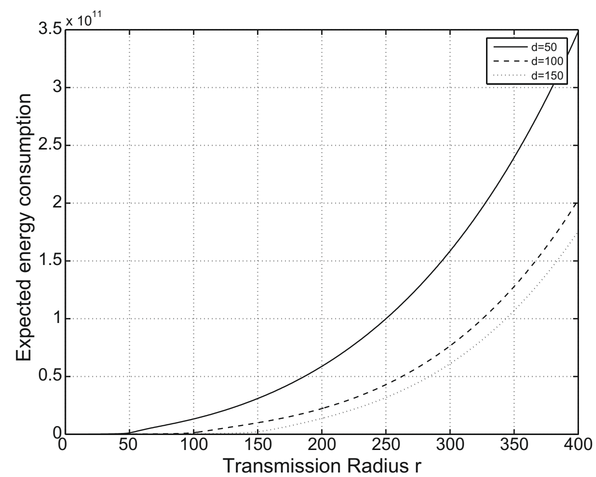

Fig. 10. A sample of total expected energy consumption.

consecutive forward nodes (including source node, then $K = 5$) are deployed in the network as shown in Fig. 8. By varying the network size we obtain three values for the distances between consecutive forward nodes ($d =$ 50, 100, and 150). Then we obtain $\overline{P}$ and $\overline{E}$ distributions for the above three scenarios as shown in Figs. 9 and 10. From them we can find that when we increase r to obtain a high delivery ratio, the expected energy consumption is also increasing. Obviously, this observation is also applicable to general case where distances between relays nodes are different.

As for how and how much to increase radii, we make the following analysis. Suppose an application which is required to guarantee the network coverage larger than α while maintaining energy efficiency, we define the *suitable transmission radii* as the minimal radii which can approximately achieve the broadcast delivery ratio no less than α. Our special case in Fig. 8 is the worst case where the successful reception of one relay node depends only on the previous relay node and there is no overlapping (coverage redundancy) on it. Therefore we could employ P^K as approximate delivery ratio in the worst case and extend to a general case as $P^K \leqslant \alpha = P^\eta \leqslant 1$ where η is defined as reception exponent and $0 \leqslant \eta \leqslant K$. When the coverage redundancy increases the value of η should decreases. As for the coverage redundancy, it can be affected by many factors, such as properties of different broadcast tree calculation algorithms, network types (omni or directional antenna networks) and network density. That is, the value of η is dependent on network settings and should be determined by measurement. From $\alpha = P^\eta$ we obtain $P = \sqrt[\eta]{\alpha}$ where P is the value of packet reception probability p. Since p is a function of transmission radius r and distance between nodes d, the computation of suitable transmission radius will be transferred to calculate the value of r when $p = \sqrt[\eta]{\alpha}$.

Fig. 11 shows a sample of packet reception probability p where we can find that if $r > d$, the scope of p is [0.5 1]; otherwise, if $r < d$, the value of p will be less than 0.5. Since high delivery ratio definitely means $\alpha \geqslant 0.5$ and therefore $p = \sqrt[\eta]{\alpha} \geqslant 0.5$, we will only employ $p = 1 - (d/r)^{q\beta}/2$ to calculate the value of r. That is $1 - (d/r)^{q\beta}/2 = \sqrt[\eta]{\alpha}$, then we obtain $r = \left[2(1 - \sqrt[\eta]{\alpha})\right]^{-1/q\beta} d$ as suitable transmission radius. To extend our analysis result to general case, we define target coefficient as $\delta = r/d = \left[2(1 - \sqrt[\eta]{\alpha})\right]^{-1/q\beta} (\delta > 1)$ illustrated in Fig. 12. We can derive transmission radii according to target coefficient δ and different distances d between all relay nodes.

In a word, rather than simply or randomly increasing transmission radius we could choose suitable radius by

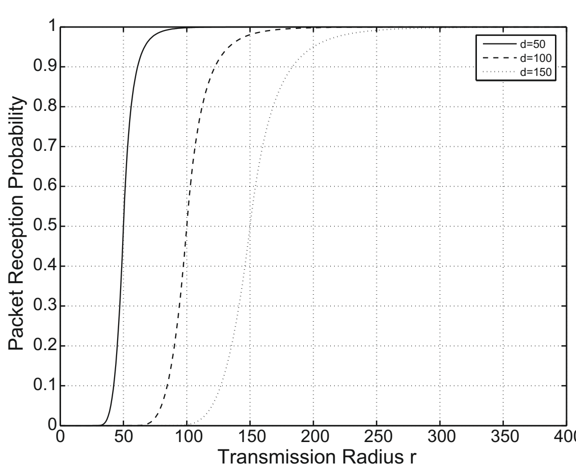

Fig. 11. A sample of packet reception probability.

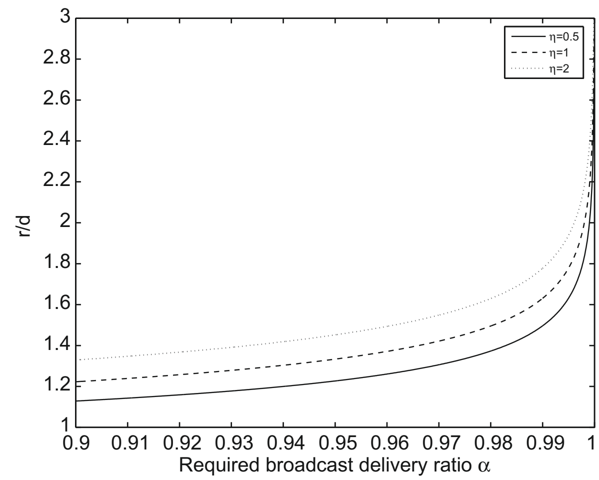

Fig. 12. Computed target coefficient based on α with $\beta = 4, q = 2$.

multiplying d with the target coefficient δ which is derived according to network coverage requirement.

Moreover, we consider not only networks with omni antennas but also directional antennas. Since transmission coverage redundancy of directional antennas is much fewer than that of omni antennas, we should estimate larger η, and then obtain larger target coefficient δ for radius determination.

5. Redundant radius broadcast protocols

In the previous section we investigated the mathematic analysis for suitable transmission radius under a realistic physical layer and derived the computation method for it. Our goal now is to design efficient broadcasting protocols with guaranteed network coverage by making use of above analysis results.

5.1. Redundant radius scheme

In the previous section, we proposed to increase transmission radius based on the distance d between relay nodes. Therefore first we should decide relay nodes and the values of d which means the broadcast tree calculation. Then we should derive "target" radii from all d and target coefficient δ, for actual data transmission, to form a buffer zone that guarantees the packet reception in the realistic physical layer. We define this mechanism as *redundant radius*.

Suppose R_m is the maximum transmission range, we define an effective range R_e as R_m/δ. The set of nodes that are reachable based on R_e is called effective neighbor set which will be used to calculate broadcast tree. In centralized protocols, all network nodes apply R_e to reconstruct virtual network topology; in localized protocols, forward nodes apply R_e to construct effective neighbor set. During broadcast tree calculation, we assume an ideal physical layer. That is, a link exists between two nodes u and v if and only if their distance is no more than transmission range r.

As shown in Fig. 13, suppose R_{calc} represents the calculated transmission radius for node S (i.e., the distance d between S and its furthest 1-hop neighbor node), in the

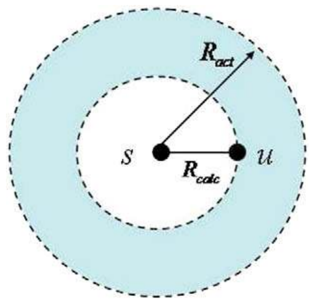

Fig. 13. Sketch map of redundant radius scheme.

redundant radius scheme we should apply longer radius $R_{act} = \delta \times R_{calc}$ as actual transmission radius. The idea of two transmission ranges is to use the "ring" which is the area bounded by two circles with transmission ranges R_{calc} and R_{act}, as a buffer zone to nullify the bad effects caused by realistic physical layer to validate the availability of logical links in the physical network.

We present two kinds of protocols that employ our redundant radius scheme (RRS):

- The first one is named RR-IP (Redundant Radius Incremental Power Protocols) and its concept is to apply RRS to incremental power philosophy based centralized protocols.
- The second one is named RR-LIP (Redundant Radius Localized Incremental Power Protocols) and these protocols extend incremental power philosophy based localized protocols.

5.2. RR-IP

The principle of incremental power philosophy is as follows. Source node calculates broadcast tree by adding nodes one at a time. In networks with fixed beam width antennas, at each step the less expensive action to add a node is selected, either by increasing the radius of an existing emission beam or by creating a new emission beam from a passive one. Omni antennas are special case of directional antennas with 2π beam width. The classical centralized protocols which employ incremental power philosophy are BIP for networks with omni antennas and DBIP for networks with directional antennas. The tree-construction process of BIP and DBIP is explained in Figs. 14 and 15, respectively.

Fig. 16a shows a simple example in which the source node 0 wants to add nodes 1, 2, and 3 to the tree. Node 1 is the closest to node 0, so it is added first; in (b), an antenna with beam width of θ_f is created between node 0 and node 1. Then we must decide which node to add next (node 2 or node 3), and which node (that is already in the tree) should be its parent. In this example, the beam from node 0 to node 1 can be extended to include both node 1 and node 3 without setting up a new beam. Compared to other choices of setting up a new beam from node 0 to node 2, or from node 1 to node 2, this method has minimum incremental power. Therefore, node 3 is added next by increasing the communication range of node 0.

Given an undirected weighted graph $G(N, A)$, where N is the set of all the nodes in G and A denotes all the edges, any node i in G is equipped with an **omni-antenna** and any other node j within its transmission range can receive packets from it, i.e., a link/edge (i, j) exists.
Suppose a broadcast tree construction is generated from a node S, i.e., S is the source node
{ /***Initialization***/
Set $T = \{S\}$, $E = \{\emptyset\}$ and $W(i) = 0$ for any node i ($1 \le i \le |N|$). Later in the following process everytime a new edge (i, j) from any node i in T to a new node j that is not in T is determinted, $W(i)$ will be updated to store i's latest transmission power, node j will be added to T and the new edge (i, j) will be added to E.
The process will not finish until all the nodes in G are included in T and the edges in E form BIP tree.
/***Tree calculation: find new edge***/
While $|T| \neq |N|$
{
for ($i \in T$)
for ($j \in (N - T)$)
Calculate the incremental power to add one edge (i, j) into BIP tree, i.e., extra energy needed to reach a node j that is not in T: $\Delta W_{ij} = d_{ij}^{\beta} - W(i)$, where d_{ij} denotes the distance between node i and j (d_{ij} should be no more than nodes' maximum transmission radius), and β is propagation path loss.
Pick an edge (i, j) for which ΔW_{ij} is minimum.
Add node j to T, i.e., $T = T \cup \{j\}$; add edge (i, j) to E, i.e., $E = E \cup \{(i, j)\}$.
Update $W(i) = W(i) + \Delta W_{ij}$.
}
Then, BIP tree is constructed as E.
}

Fig. 14. Pseudo code of BIP tree-construction.

In (c), finally, node 2 must be added to the tree. Three possibilities are respectively to set up a new beam from node 0, node 1, or node 3. We assume that node 3 has the minimum distance to node 2. Then in (d) we set up a new beam from node 3 to node 2.

Centralized protocols calculate broadcast tree on the whole network nodes' location information. Source node includes all the forward nodes' relay instructions into packet. Each node that receives the packet for the first time will check the packet. If a node finds relay instruction for itself, this node will forward the packet.

We apply the *Redundant Radius Scheme* to centralized protocols, such as BIP and DBIP. We modify some parts of them, so that each node can increase its radius up to the target radius when a retransmission is needed.

Source node s has to manage two tables, $T(s)$ and $T'(s)$. The first one, $T(s)$, stores the link information of the whole network based on maximum transmission radius R_m. The table $T'(s)$ also stores link information while it's based on smaller effective range R_e of R_m/δ. Our RR-IP protocols calculate broadcast tree with the table $T'(s)$. Suppose R_{calc} represents the distance between emitting nodes in calculated broadcast tree, RR-IP will employ longer $R_{act} = \delta \times R_{calc}$ as actual transmission radius.

Given an undirected weighted graph $G(N)$, where N is the set of all the nodes in G, any node i in G is equipped with a **fixed-beamwidth directional antenna**, the orientation of which can be shifted to any direction and any other node j within its coverage area can receive packets from it, i.e., a link/edge (i, j) exists.
Suppose a broadcast tree construction is generated from a node S, i.e., S is the source node
{ /*****Initialization*****/
Set $T = \{S\}$, $E = \{\emptyset\}$, $W(i) = 0$ and $\alpha(i) = 0$ for any node i $(1 \le i \le |N|)$. Later in the following process everytime a new edge (i, j) from any node i in T to a new node j that is not in T is determinted, $\alpha(i)$ will be updated to store the orientation of node i's beam, $W(i)$ will be updated to store i's latest transmission power, node j will be added to T and the new edge (i, j) will be added to E. The process will not finish until all the nodes in G are included in T and edges in E form DBIP tree.
/*****Tree calculation: find new edge*****/
While $|T| \ne |N|$
{
To create an edge $(i, j) \in T \times (N - T)$, there are two ways to include a node j which is not in T:
1) for a node i in T whose $W(i) = 0$, creat a beam aiming to node j with a fixed beam width θ_f;
2) for a node i in T whose $W(i)! = 0$, extend the existing beam with the orientation stored in $\alpha(i)$ to cover node j by increasing transmission radius.
for $(i \in T)$
for $(j \in (N - T))$
Calculate the incremental power ΔW_{ij} to add one edge (i, j) into DBIP tree, i.e., extra energy needed to reach a node j that is not in T:
if method 1) is used, $\Delta W_{ij} = d_{ij}^{\beta}\frac{\theta_f}{2\pi} - W(i) = d_{ij}^{\beta}\frac{\theta_f}{2\pi}$,
where d_{ij} denotes the distance between node i and j (d_{ij} should be no more than nodes' maximum transmission radius), and β is path loss;
if method 2) is used, $\Delta W_{ij} = d_{ij}^{\beta}\frac{\theta_f}{2\pi} - W(i)$.
Pick an edge (i, j) for which ΔW_{ij} is minimum.
Add node j to T, i.e., $T = T \cup \{j\}$; add edge (i, j) to E, i.e., $E = E \cup \{(i, j)\}$.
Update $W(i) = W(i) + \Delta W_{ij}$.
If method 1) is used, $\alpha(i)$ is used to store the orientation of node i.
}
Then, DBIP tree is constructed as E.
}

Fig. 15. Pseudo code of DBIP tree-construction.

RR-BIP is corresponding to BIP and RR-DBIP is corresponding to DBIP. Experimental results for them are given in Section 6.

5.3. RR-LIP

The main idea of RR-LIP is to apply Redundant Radius Scheme to localized incremental power philosophy based protocols.

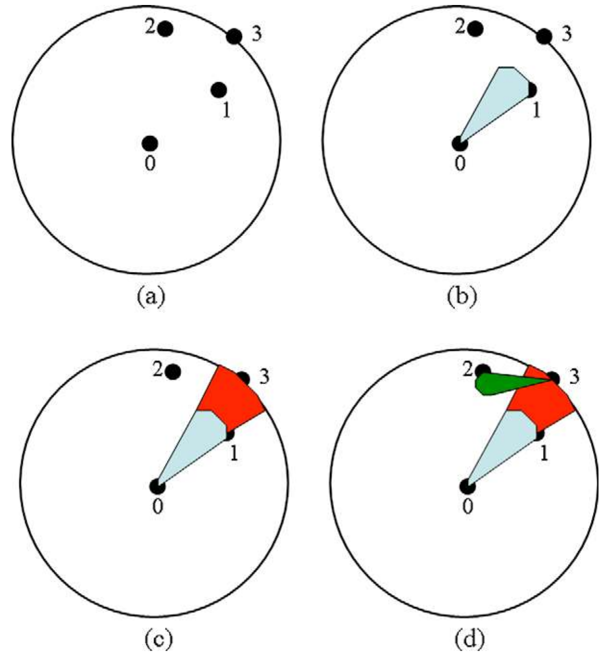

Fig. 16. Example of DBIP tree-construction.

Fig. 17 shows the principle of localized algorithms.

Localized protocols calculate broadcast tree in a distributed way. Source node *s* first calculates localized broadcast tree with its localized neighbors information and includes forward instruction in packet. Node *u* which receives the packet for the first time will check the packet. If a node finds relay or rebroadcast instruction for it, this node will forward packet, or set up its own localized neighbor information and act as source node.

We apply the *Redundant Radius Scheme* to localized protocols, such as LBIP and LDBIP. We modify some parts of them, so that each node increases its radius up to the target radius when an emission is needed.

Any node u who is in charge of calculating localized broadcast tree has to manage two tables, $LT(u)$ and $LT'(u)$. The first one, $LT(u)$, stores the link information among neighbor nodes based on maximum transmission radius R_m. The table $LT'(u)$ also stores link information of neighbor nodes while it is based on smaller effective range R_e of R_m/δ. Our RR-LIP protocols calculate broadcast tree with the table $LT'(u)$. Suppose R_{calc} represents the distance between emitting nodes in calculated broadcast tree, RR-LIP will employ longer $R_{act} = \delta \times R_{calc}$ as actual transmission radius. RR-LBIP is corresponding to LBIP and RR-LDBIP is to LDBIP. Experimental results are given in next section.

6. Performance evaluation

In this section, we give experimental results for our proposed protocols RR-IP and RR-LIP and comparisons with existing protocols.

```
Randomly select source node S
For source node S :
{ /***Source node's local calculation***/
  Compute its local broadcast tree;
  Set up broadcast packet B;
  Include m hops relay instructions in B;
  Include m hops neighbors id in B;
  Include mth hop relay nodes' id in B;
  Send B to each of its one hop neighbors;
}
For any node U (except S):
if(node U receives packet B){
  if(the first time){
    Inspect packet B;
    if(there is relay instruction for U){
      if(U'id exists in mth hop relay nodes id){
        Record all relay instructions for U;
        /*Neighbor nodes elimination scheme*/
        Check included covered nodes id;
        While((id!=U's id)&&(id not exist in relay info))
          if (id ∈ U's local neighbors list)
            delete this node record from U's neighbors list;
        /***U's Local calculation***/
        Refer recorded relay instructions;
        Use U's modified local neighbors list;
        Computes U's local broadcast tree;
        Act as source node;
      }elseif(U's id does not exist in mth hop relay id)
        Only relay packet B as recorded relay instructions.
    }elseif(there is no relay instruction for U)
      Do nothing;
  }else
    Simply drop packet B.
}
```

Fig. 17. Localized algorithms.

6.1. Simulation settings

We use *ns2* as our simulation tool and assume AT&T's Wave LAN PCMCIA card as the wireless node model with parameters as listed in Table 3. As for system model, we employ 802.11 MAC protocol and in physical layer we apply the shadowing model. Table 4 shows the parameters of the shadowing model. It is clear that in centralized algorithms broadcast tree-construction is based on the whole network topology and in localized algorithms it is based on local topology, such as 1 hop neighborhood local view constructed by neighbors' location information. In static networks, in protocol initialization period each node floods its location information to the whole network, the global network information can then be achieved for centralized algorithms; for localized algorithms, each node can just broadcasts its information to neighbors with maximum transmission radius. However, in mobile environment, it is too difficult to get accurate global network topology, that is, centralized algorithms are not suitable. It is well-known that for localized algorithms mobile nodes can periodically advertise their presence to neighbors and each node can still grasp its neighborhood local view by collecting those so called "Hello" messages. To improve the accuracy of neighborhood local view, mobility management/tracking schemes could be added, such as predictive neighborhood tracking scheme which is proposed in our other work [31], and then our scheme can still be utilized to determine relay sets and corresponding radii. As our goal in this paper is focusing on demonstrating the effectiveness of our scheme in mitigating the poor network coverage problem caused by realistic physical layer effects, nodes in our simulation networks are static.

In addition, in our simulations the network is with fixed size and nodes are always randomly placed. The number of nodes is variable to obtain different network density. The broadcast traffic rate is 1 packet per second with 64 bytes per packet. Each packet is issued from a randomly selected node. Simulation parameters are shown in Table 5.

To evaluate the network coverage of broadcast protocols, we define the Broadcast Delivery Ratio (*BDR*) as *the average percentage of nodes in network that receive broadcasted message from one broadcast task*. Similarly, to evaluate the energy efficiency of broadcast protocols, we define the Energy Consumption Ratio (*ECR*) as the average energy consumption for one broadcast task of the considered

Table 3
Parameters for wireless node model.

Items	Value
Frequency	2.4 GHz
Maximum transmission range R_m	250 m
Maximum transmit power	0.2818 W
Receiving power C_r	0.395 W
Transmitting power C_e	0.660 W
Omni antenna receiver/transmitter gain	0 dB
Fixed beam width of directional antennas θ_f	60°
Directional antenna receiver/transmitter gain	12 dB
MAC protocol	802.11
Propagation model	Shadowing

Table 4
Parameters for shadowing model.

Items	Value
Path loss exponent	4.0
Gaussian random variable	Zero mean and standard deviation as 4.0 dB
Seed for RNG	1
Reference distance	1.0 m

Table 5
Simulation parameters.

Items	Value
Simulation Network Size	900×900 m^2
Simulation time	50 s
Packet size	64 Bytes
Transmission delay	25 μs
Broadcast traffic rate	1 packet/s

protocol compared to the energy that would have been spent by a blind flooding (each node retransmits once with maximum emission range). The calculation of *ECR* on simulation results would be then:

$$ECR = \frac{E_{protocol}}{E_{flooding}} \times 100\%, \quad (8)$$

where $E_{protocol}$ represents the consumed energy when efficient broadcast scheme is applied, and $E_{flooding}$ denotes that when flooding is used. In addition, since topology information is achieved during initialization period, when the whole simulation time is long enough to make initialization period neglectable, the initialization energy consumption could then be neglected.

In the following performance evaluation work, we show the *BDR* and *ECR* performance of each proposed protocol respectively to verify our proposed RR-IP and RR-LIP in guaranteeing the required network coverage α while keeping energy efficiency.

6.2. Simulation results for RR-IP

Our redundant radius scheme (RRS) is to emit with "target" radii, i.e., obeying $r/d = \delta$ where δ is target coefficient and d is the distance between transmitter and receiver. By applying RRS to incremental power philosophy based centralized protocols, we obtain RR-IP.

To verify the correctness of our choice for δ, we vary transmission radii with various coefficient r/d and observe protocol performance in terms of packet delivery ratio and energy consumption, which is shown in Figs. 18 and 20. Specially, when $r/d = 1.0$ the protocol keeps origin, and its performance could be compared to that of our RR-IP.

The main task of our evaluation is to show that the calculated "target" coefficient in our scheme for specific network condition, e.g., with certain network density (nodes number N) and required network coverage α, can help the protocol RR-IP approximately achieve the required α while among all r/d values which can achieve network coverage more than α, our δ causes minimum energy consumption (*ECR*). In addition, to make our demonstration more clearly from Figs. 18 and 20 we pick the performances when network density $N = 60$ and 90 as examples and make comparisons in Tables 6 and 7.

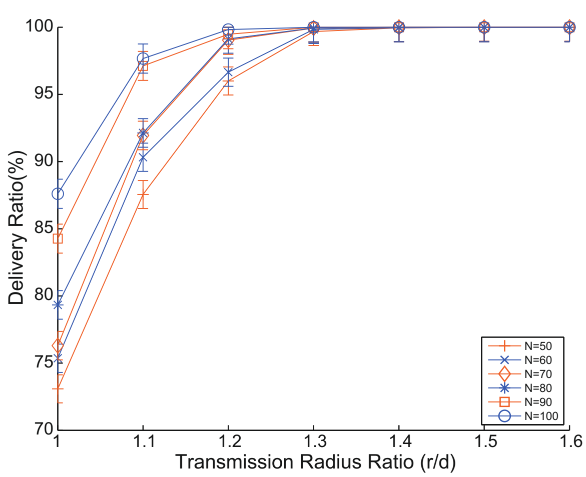

Fig. 18. *BDR* observation for BIP with various r/d.

Table 6
BDR evaluation for RR-BIP.

N	Choose η	Required α	Calculated δ	*BDR*	*BDR* $-\ \alpha$
60	0.4	0.90	1.1	0.9032	0.0032
60	0.4	0.95	1.2	0.9665	0.0165
60	0.4	0.99	1.5	0.9984	0.0084
90	0.2	0.95	1.1	0.9712	0.0212
90	0.2	0.99	1.3	1.0000	0.0100

Table 7
BDR evaluation for RR-DBIP.

N	Choose η	Required α	Calculated δ	*BDR*	*BDR* $-\ \alpha$
60	45	0.96	$\approx$2.5	0.9627	0.0027
90	40	0.92	2.0	0.9360	0.0160
90	40	0.99	2.5	1.0000	0.0100

First, we show the effectiveness of redundant radius scheme ($r/d > 1.0$) on improving broadcast delivery ratio. Figs. 18 and 20, respectively show *BDR*s of BIP and DBIP with various r/d. It is obvious that when $r/d > 1.0$ the *BDR* is higher than that when $r/d = 1.0$. And as r/d increases, the *BDR* value also increases. In dense networks the *BDR* of original BIP ($r/d = 1.0$) is still less than 90% and that of original DBIP is even less than 30%. However, despite of network density the *BDR* of BIP with redundant radius, i.e., $r/d > 1.0$, is almost larger than 90% and that of DBIP with redundant radius is also more than 60%. As we have analyzed in Section 4, the coverage redundancy of networks with directional antennas is much less than that of omni antennas. In Fig. 18 when r/d reaches 1.5, despite of network density, the *BDR* value of BIP-based protocol is almost 100%; however, in Fig. 20 that of DBIP-based protocol is only within 60–80%.

Next, we demonstrate the effectiveness of our proposed RR-IP protocol, i.e., employing target r/d of δ, in achieving the required network coverage α. We propose to determine δ as $\left[2(1-\sqrt[\eta]{\alpha})\right]^{-1/q\beta}$ and in our simulation $\beta = 4$ and $q = 2$ then $\delta = \left[2(1-\sqrt[\eta]{\alpha})\right]^{-1/8}$. Since RR-BIP is a centralized protocol for omni antenna networks, we choose small reception exponent η of around 0.4 in relatively scarce networks ($N = 60$) and around 0.2 in relatively dense networks ($N = 90$). As we have declared that larger η should be estimated to achieve larger δ for networks with directional antennas, for RR-DBIP we choose η around 45 when $N = 60$ and around 40 when $N = 90$. According to the required network coverage α we calculate the corresponding target coefficient δ, respectively in Figs. 19 and 21 and check the corresponding *BDR* value when $r/d = \delta$ respectively in Figs. 18 and 20. We make lists in Tables 6 and 7 for convenient comparison. From Tables 6 and 7 we can see that by applying δ calculated from the proposed formula we can achieve the required delivery ratio and the difference is limited within 0.022.

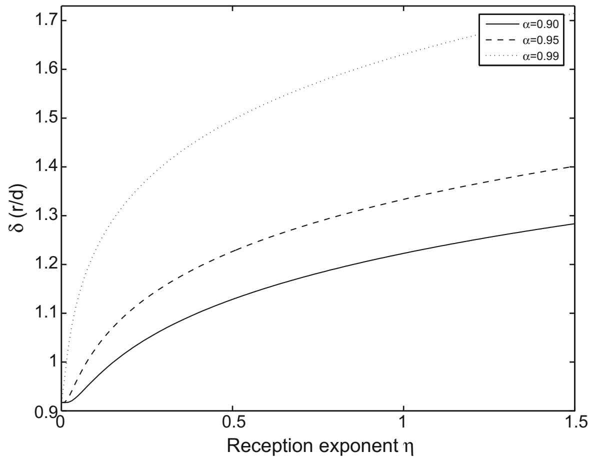

Fig. 19. δ calculation for RR-BIP.

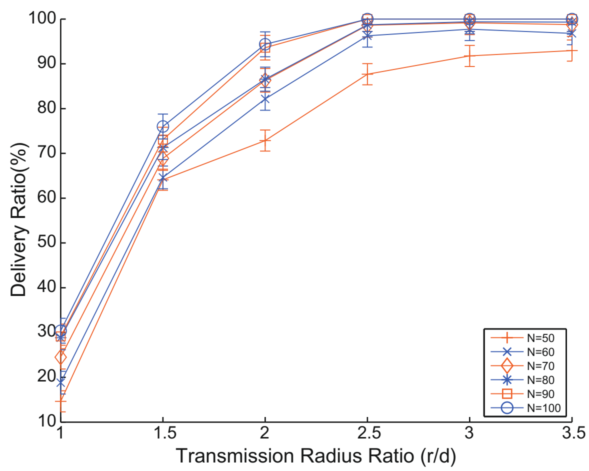

Fig. 20. *BDR* observation for DBIP with various r/d.

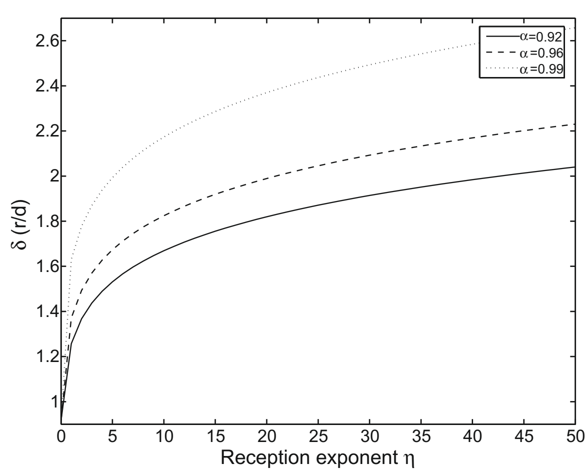

Fig. 21. δ calculation for RR-DBIP.

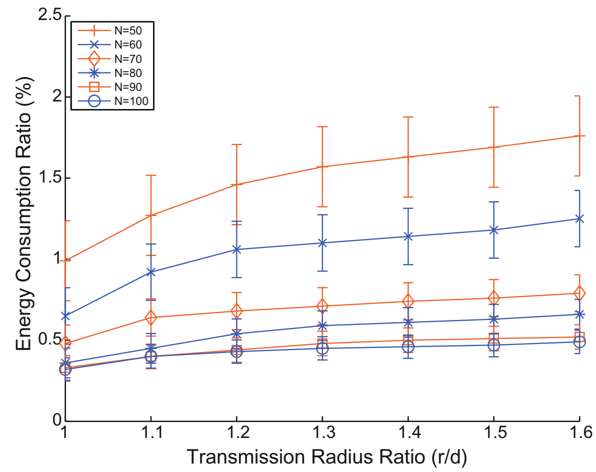

Fig. 22. *ECR* observation for BIP with various r/d.

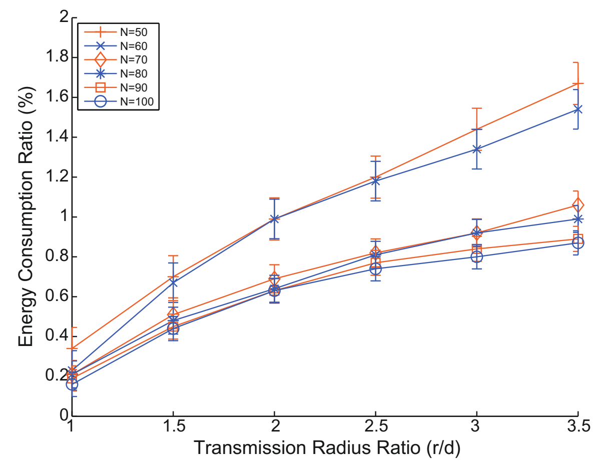

Fig. 23. *ECR* observation for DBIP with various r/d.

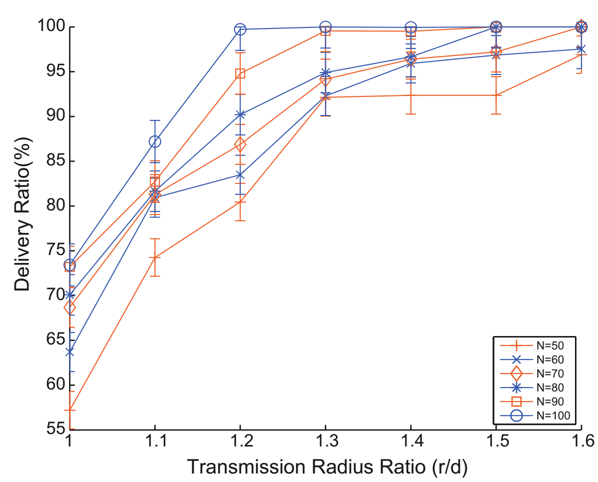

Fig. 24. *BDR* observation for LBIP with various r/d.

Table 8
BDR evaluation for RR-LBIP.

N	Choose η	Required α	Calculated δ	BDR	$BDR-\alpha$
60	1.2	0.92	1.3	0.9229	0.0029
60	1.2	0.96	1.4	0.9592	0.0008
60	1.2	0.98	1.5	0.9686	0.0114
90	0.3	0.96	1.2	0.9480	0.0120
90	0.3	0.98	1.3	0.9956	0.0156

Table 9
BDR evaluation for RR-LDBIP.

N	Choose η	Required α	Calculated δ	BDR	$BDR-\alpha$
60	40	0.92	2.0	0.9240	0.0040
90	20	0.96	2.0	0.9733	0.0133
90	20	0.99	2.5	0.9955	0.0055

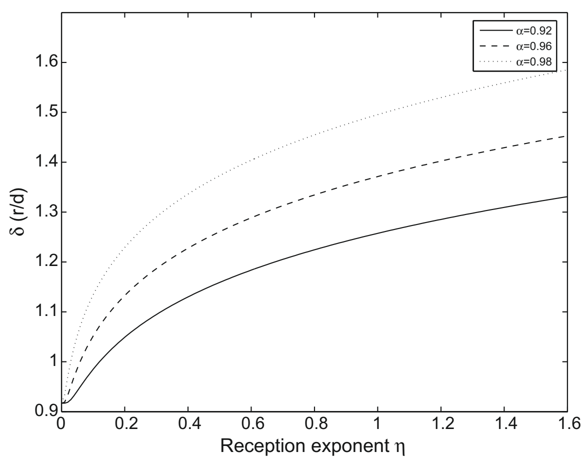

Fig. 25. δ calculation for RR-LBIP.

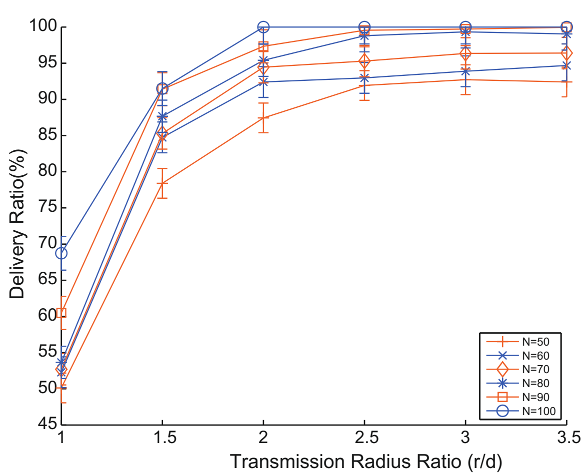

Fig. 26. *BDR* observation for LDBIP with various r/d.

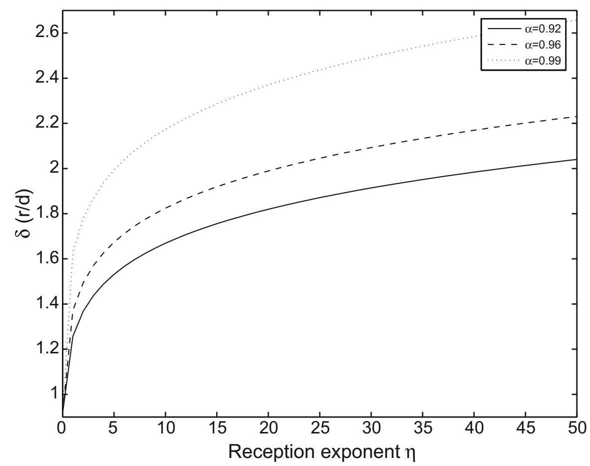

Fig. 27. δ calculation for RR-LDBIP.

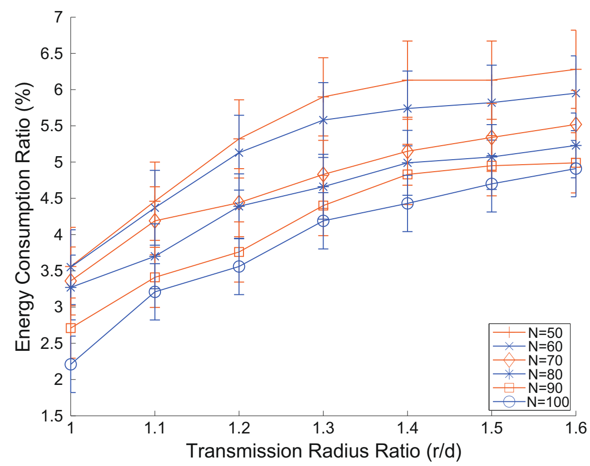

Fig. 28. *ECR* observation for LBIP with various r/d.

Finally, we can argue that our proposal can serve as suitable solution since with calculated target radii our protocols can approximately achieve the required network coverage with minimal energy consumption. Fig. 22 displays the energy consumption of redundant BIP protocol with r/d values varying from 1.1 to 1.6. Fig. 23 displays that of redundant DBIP with r/d values varying from 1.5 to 3.5. We can see that as r/d increases *ECR* always increases. Therefore, the minimal value of r/d which can help achieving required α should be suitable choice. In previous analysis we have proved that the δ computed based on our proposed formula can fulfill above requirement which means our solution is suitable.

6.3. Simulation results for RR-LIP

RR-LIP is the localized protocols which employ our RRS scheme. RR-LBIP and RR-LDBIP are based on LBIP and LDBIP, respectively.

Similarly, Figs. 24 and 26, respectively show that LBIP and LDBIP with redundant radii, i.e., $r/d > 1.0$, have higher

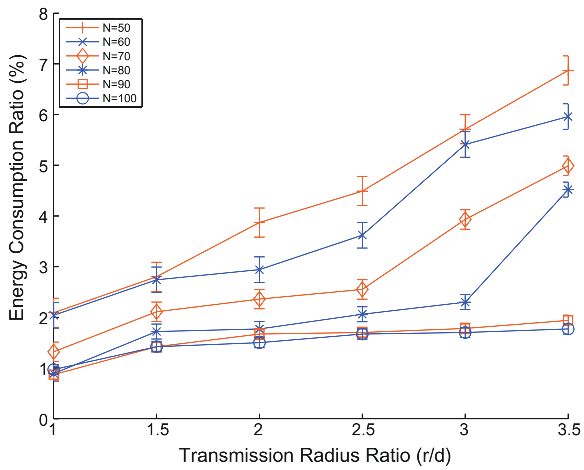

Fig. 29. *ECR* observation for LDBIP with various r/d.

BDR values than LBIP and LDBIP with $r/d = 1.0$ which demonstrates again the effectiveness of redundant radius scheme in improving network coverage.

To demonstrate the effectiveness of our proposed localized RR-LIP protocols, i.e., employing target r/d of δ, in achieving the required network coverage α, we make *BDR* lists for RR-LBIP and RR-LDBIP in Tables 8 and 9, respectively. In addition, the calculation of δ for RR-LBIP and RR-LDBIP is respectively shown in Figs. 25 and 27. They show again that the δ calculated from proposed formula is also effective for localized broadcast protocols in achieving right the required *BDR*.

Figs. 28 and 29 demonstrate that in our localized protocols as r/d increases basically *ECR* also increases. Since the computed δ based on our formula can help achieving right the required α, it validates again that our solution is suitable to balance the required network coverage and energy efficiency.

7. Conclusions

We presented the trade-off between improving network coverage and minimizing energy consumption in broadcasting operations. We then showed how the physical layer impacts the selection of transmission radius and proposed the "redundant radius" scheme. The experimental results we have presented illustrate the effectiveness of our scheme.

In our future work, we plan to represent the trade-off between the two design metrics of energy efficiency and network coverage more precisely as a bi-objective integration program model, that is, assign important factors a_1 and $a_2 (a_1 + a_2 = 1)$ for each of them. Formulations of two metrics and an optimization problem could then be defined and investigated.

References

[1] S. Basagni, M. Conti, S. Giordano, I. Stojmenovi, Mobile Ad Hoc Networking, first ed., IEEE Press/Wiley, 2004.
[2] J.M. Kahn, R.H. Katz, K.S.J. Pister, Next century challenges: mobile networking for smart dust, in: Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), Seattle, USA, 1999, pp. 271–278.
[3] S. Giordano, Mobile ad hoc networks, Handbook of Wireless Networks and Mobile Computing (2002) 325–346.
[4] G.J. Pottie, W.J. Kaiser, Wireless integrated network sensors, Communications of the ACM 43 (2000) 51–58.
[5] J.E. Wieselthier, G.D. Nguyen, A. Ephremides, On the construction of energy-efficient broadcast and multicast trees in wireless networks, in: Proceedings of 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), Tel Aviv, Israel, vol. 2, 2000, pp. 585–594.
[6] J.E. Wieselthier, G.D. Nguyen, A. Ephremides, Energy-limited wireless networking with directional antennas: the case of session-based multicasting, in: Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), New York, USA, vol. 1, 2002, pp. 190–199.
[7] F. Ingelrest, D. Simplot-Ryl, I. Stojmenovic, Localized broadcast incremental power protocol for wireless ad hoc networks, Wireless Networks 14 (3) (2008) 309–319.
[8] H. Xu, M. Jeon, L. Shu, X. Wu, J. Cho, S. Lee, Localized energy-aware broadcast protocol for wireless networks with directional antennas, in: Proceedings of the 2nd International Conference on Embedded Software and Systems (ICESS), Xian, China, 2005, pp. 696–707.
[9] M. Takai, J. Martin, R. Bagrodia, Effects of wireless physical layer modeling in mobile ad hoc networks, in: Proceedings of the 2nd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC), Long Beach, California, USA, 2001, pp. 87–94.
[10] J. Broch, D.A. Maltz, D.B. Johnson, Y.-C. Hu, J. Jetcheva, A performance comparison of multi-hop wireless ad hoc network routing protocols, in: Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), Dallas, Texas, USA, 1998, pp. 85–97.
[11] I. Stojmenovic, A. Nayak, J. Kuruvila, F.J. Ovalle-Martinez, E. Villanueva-Pena, Physical layer impact on the design and performance of routing and broadcasting protocols in ad hoc and sensor networks, Computer Communications 28 (10) (2005) 1138–1151.
[12] J. Kuruvila, A. Nayak, I. Stojmenovic, Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic physical layer, IEEE Journal on Selected Areas in Communications 23 (6) (2005) 1267–1275.
[13] J. Kuruvila, A. Nayak, I. Stojmenovic, Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer, Journal of Parallel and Distributed Computing, Special Issue on Algorithms for Wireless and Ad-hoc Networks 66 (4) (2006) 499–506.
[14] T. Oliveira, F. Greve, The node reliability approach to broadcasting in manets: raising reliability with low end-to-end delay, in: Proceedings of the 4th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS), Pisa, Italy, 2007, pp. 1–9.
[15] F. Li, K. Wu, Reliable, distributed and energy-efficient broadcasting in multi-hop mobile ad hoc networks, in: Proceedings of the 27th Annual IEEE Conference on Local Computer Networks (LCN), Tampa, Florida, USA, 2002, pp. 761–769.
[16] W. Lou, J. Wu, A reliable broadcast algorithm with selected acknowledgements in mobile ad hoc networks, in: Proceedings of the Global Telecommunications Conference (GLOBECOM), San Francisco, USA, 2003, pp. 3536–3541.
[17] W. Lou, J. Wu, Toward broadcast reliability in mobile ad hoc networks with double coverage, IEEE Transactions on Mobile Computing 6 (2) (2007) 148–163.
[18] F. Ingelrest, D. Simplot-Ryl, I. Stojmenovic, Optimal transmission radius for energy efficient broadcasting protocols in ad hoc and sensor networks, IEEE Transactions on Parallel and Distributed Systems 17 (6) (2006) 536–547.
[19] P. Bose, P. Morin, I. Stojmenovic, J. Urrutia, Routing with guaranteed delivery in ad hoc wireless networks, Wireless Networks 7 (2001) 609–616.
[20] T. Chu, I. Nikolaidis, Energy efficient broadcast in mobile ad hoc networks, in: Proceedings of the Ad-Hoc Networks and Wireless (ADHOC-NOW), Toronto, Canada, 2002, pp. 177–190.
[21] W. Peng, X.-C. Lu, On the reduction of broadcast redundancy in mobile ad hoc networks, in: Proceedings of the International Symposium on Mobile and Ad Hoc Networking and Computing (MOBIHOC), Boston, Massachusetts, USA, 2000, pp. 129–130.
[22] A. Qayyum, L. Viennot, A. Laouiti, Multipoint relaying for flooding broadcast messages in mobile wireless networks, in: Proceedings of the 35th Annual Hawaii International Conference on System Sciences (HICSS), Hawaii, USA, 2002, pp. 3866–3875.

[23] J. Wu, H. Li, A dominating-set-based routing scheme in ad hoc wireless networks, Telecommunication Systems 18 (2001) 13–36.
[24] T.S. Rappaport, Wireless Communications, second ed., Principles and Practice, IEEE Press, 1996.
[25] T. Rappaport, Wireless Communications, Principles and Practice, Prentice-Hall, PTR, Upper Saddle River, 2002.
[26] K. Fall, K. Varadhan, The ns Manual, The VINT Project, UCB, LBL, USC/ISI and Xerox PARC, 2002.
[27] R. Hekmat, P.V. Mieghem, Interference power sum with log-normal components in ad-hoc and sensor networks, in: Proceedings of the 3rd International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WIOPT), Trentino, Italy, 2005, pp. 174–182.
[28] S. Banerjee, A. Misra, Minimum energy paths for reliable communication in multi-hop wireless networks, in: Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC), Lausanne, Switzerland, 2002, pp. 146–156.
[29] S. Guo, O.W.W. Yang, Antenna orientation optimization for minimum energy multicast tree-construction in wireless ad hoc networks with directional antennas, in: Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC), Tokyo, Japan, 2004, pp. 234–243.
[30] V. Rodoplu, T.H. Meng, Minimum energy mobile wireless networks, IEEE Journal on Selected Areas in Communications 17 (8) (1999) 1333–1344.
[31] H. Xu, J.J. Garcia-Luna-Aceves, Neighborhood tracking for mobile ad hoc networks, Computer Networks, Special Issue on Autonomous Systems, Elsevier. doi:10.1016/j.comnet.2008.12.021.

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