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Publication Date

2008-11-30

Peer reviewed

Efficient Broadcast in Wireless Ad Hoc and Sensor Networks with a Realistic Physical Layer

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Abstract— To minimize energy consumption efficient broadcasting in ad hoc and sensor networks aims to select small sets of forwarding nodes and to minimize the transmission radius. However, the physical-layer characteristics of radio links are such that chosen receivers which may not be able to decode packets sent to them, even without multiple access interference. We present an analytical model to show that the transmission radius 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 radii*, 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. The effectiveness of the proposed scheme in improving network coverage is validated analytically and by simulation.

I. INTRODUCTION

Broadcasting is an indispensable operation in wireless sensor and ad hoc networks. It is needed for route discovery, information dissemination, publication of services, data gathering, task distribution, time synchronization, and so on. Given that untethered devices rely on batteries with limited capacity, one of the most important criteria when designing communication protocols is energy efficiency. Hence, a key objective of broadcasting algorithms and protocols is to minimize energy consumption. Tree-based broadcasts provide the best energy efficiency, because they select the smallest number of forwarding nodes. Because energy consumption depends on transmission ranges, a straightforward way to preserve energy is to limit the transmission radii to those distances needed to reach selected neighboring nodes. However, while transmission radius adaptation has been explored in many broadcasting schemes in the past, they have assumed an ideal physical-layer model in which nodes within a given transmission range receive packets with probability 1. This, of course, is not realistic in most practical situations. In reality, the received power levels may show significant variations around the mean power and nodes can decode packets with probabilities smaller than 1. As a consequence, tree-based broadcasting schemes that minimize the number of forwarding nodes may suffer from poor network coverage.

The work presented in this paper is inspired by recent research work in [1], [2], [3], [4]. Takai et al. [1] showed the importance of the physical layer, even though the protocols evaluated do not directly interact with the physical layer. Stojmenovic et al. [2], [3], [4] 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. 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 and sensor network with realistic physical layer and proposed a concept of dominating sets to be used in broadcasting process.

Section II presents some preliminaries and the system model we assume in our study, and Section III presents an analytical model showing that the delivery ratio can be increased by lengthening the transmission radii of forwarding nodes; however, this is attained by also increasing energy consumption at each such node. 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 the required network coverage.

Section IV proposes our “redundant radius” mechanism for efficient broadcasting, which makes use of the approximate radii calculation. After neighborhood information is collected, a smaller neighborhood range is used to calculate a broadcast tree; and then a longer radii is used as the actual transmission radii, which is based on the approximate transmission radii to form a buffer zone that guarantees the availability of logical links in the network. Section V addresses the effectiveness of the proposed scheme in improving the network coverage using simulations.

II. PRELIMINARIES AND SYSTEM MODEL

Because of multipath effects [5] caused by reflection, diffraction and scattering, the signal level obtained at a receiver is actually a 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. The above 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 problems cannot be avoided completely;

therefore, network protocols design must take such effects into consideration.

We employ a widely used physical layer model, the log-normal shadowing [6], to simulate the multipath effect. In reality, the received power levels may show significant variations around the area mean power [7]. 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. 1).

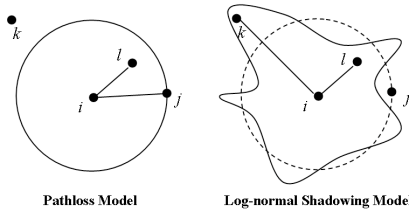


Fig. 1. Coverage comparison with ideal physical layer model.

The shadowing model consists of two parts. The first one is known as path-loss model and predicts the mean received power at distance d , denoted by $\overline{W}_r(d)$. It uses a close-in distance d_0 as a reference. $\overline{W}_r(d)$ is computed relative to $W_r(d_0)$ as follows

$$\frac{W_r(d_0)}{\overline{W}_r(d)} = \left(\frac{d}{d_0}\right)^\beta, \quad (1)$$

where β is the path loss exponent with value between 2 in free space to 6 in heavily built urban areas [8] and $W_r(d_0)$ can be computed from free space model. The path loss is usually measured in dB . From Eq. (1) we have

$$\left[\frac{W_r(d)}{W_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right). \quad (2)$$

The second part reflects the variation of the received power at certain distance. It is a log-normal random variable, or it is of Gaussian distribution if measured in dB . The overall shadowing model is represented by

$$\left[\frac{W_r(d)}{W_r(d_0)}\right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB}, \quad (3)$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB} which is called the shadowing deviation and is also obtained by measurement.

In the IEEE 802.11 MAC protocol, if a packet is broadcast, no acknowledgments or retransmissions are sent. Therefore, we apply the end-to-end retransmissions (EER) operating model [9] for our analysis: the individual links do not provide link-layer retransmissions and error recovery.

We use a directional antenna propagation model [10] as shown in Fig. 2, where the beamwidth of each antenna cannot be adjusted, i.e., θ_f ($0 \leq \theta_f < 2\pi$), is fixed for any node and the orientation of each antenna, φ ($0 \leq \varphi < 2\pi$), can be shifted to any desired direction to provide connectivity to a subset of the nodes within communication range. In fact, an omni-antenna can be regarded as a special case with 2π as its beam width.

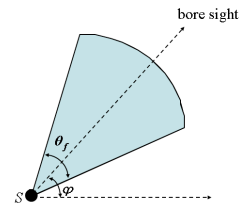


Fig. 2. Directional antenna propagation model.

TABLE I
NOTATIONS USED IN THIS PAPER.

Notation	Description
β	Path loss.
N	Total number of nodes in network.
K	Number of forward nodes (including source node), less than N .
d	Distance variable between two nodes.
A	Network area.
θ_f	Antenna beam width for any transmission session.
D	Network density.
r	Transmission radii variable for any forward node.
$D(r)$	Transmission coverage (average neighbors number with radii 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 radii value for i th forward node.
p	Packet reception probability variable function.
P_i	Packet reception probability value for i th forward node.
\overline{P}	Expected delivery ratio for one broadcast task.
\overline{E}	Total expected energy consumption for one broadcast task.

III. ANALYTICAL MODEL

A. Energy Consumption Model

We assume that all packets are of the same size (number of bits) and now that two nodes are at distance d , but a packet is sent with transmission radii r . In the most commonly used energy model, the energy consumption for transmission is $r^\beta \frac{\theta_f}{2\pi} + C_e$, where θ_f represents antennas beam width (for omni antennas, 2π) and C_e represents an overhead due to signal processing. Nodes also consume energy upon the reception of a message. This consumption, denoted as C_r , is constant, regardless of the distance between the emitter and the receiver. In a word, for one transmission, assume there are n nodes within transmission range, the energy consumption will be $r^\beta \frac{\theta_f}{2\pi} + C_e + n \times C_r$.

The model of $r^4 + 10^8 + n \times \frac{2}{3} \times 10^8$ is derived for omni antenna emission from the work by Rodoplu and Meng [11] where $\beta = 4$, $C_e = 10^8$, $C_r = \frac{2}{3} \times 10^8$, and it is expected to be realistic enough to be used as a reference for theoretical analysis because a lot of related work, such as [12], employed this model. These values are expressed in arbitrary units and can be converted into any given units by using a corresponding

multiplication factor.

B. Computation of Suitable Transmission Radii

Table I shows notations used in this paper. Let us consider a rectangular area A where N nodes are randomly placed. D is the network density defined as $D = N \times \frac{\pi R_m^2}{A}$ where R_m is the maximum transmission range. Assume in one broadcast task, source node emits one packet with a transmission radii R_1 . There exist $K - 1$ consecutive forward nodes and their packet reception probability values are P_1, P_2, \dots, 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 radii values are R_2, \dots, R_K respectively. For any node with transmission radii r , we can calculate its transmission neighborhood density (average neighbors number), denoted by $D(r)$, as $D(r) = D \times \frac{\pi r^2}{\pi R_m^2} = \frac{Dr^2}{R_m^2}$.

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

$$\begin{aligned} \bar{E} &= \left(R_1^\beta \frac{\theta_f}{2\pi} + C_e + \frac{DR_1^2}{R_m^2} C_r \right) + P_1 \left(R_2^\beta \frac{\theta_f}{2\pi} + C_e + \frac{DR_2^2}{R_m^2} C_r \right) + P_1 P_2 \left(R_3^\beta \frac{\theta_f}{2\pi} + C_e + \frac{DR_3^2}{R_m^2} C_r \right) + \dots \\ &+ P_1 P_2 \dots P_{K-1} \left(R_K^\beta \frac{\theta_f}{2\pi} + C_e + \frac{DR_K^2}{R_m^2} C_r \right) \\ &= \sum_{i=1}^K \left(\prod_{j=0}^{i-1} P_j \right) \left(R_i^\beta \frac{\theta_f}{2\pi} + C_e + \frac{DR_i^2}{R_m^2} C_r \right), \end{aligned} \quad (4)$$

where $P_0 = 1$.

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

$$\begin{aligned} \bar{P} &= \frac{P_1 \frac{DR_1^2}{R_m^2} + P_1 P_2 \frac{DR_2^2}{R_m^2} + \dots + P_1 \dots P_K \frac{DR_K^2}{R_m^2}}{N} \\ &= \frac{\sum_{i=1}^K \left(\prod_{j=1}^i P_j \right) \frac{DR_i^2}{R_m^2}}{N}. \end{aligned} \quad (5)$$

Because of coverage redundancy, (as illustrated in Fig. 3,

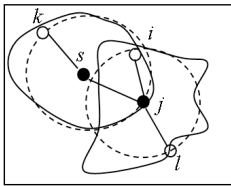


Fig. 3. An example of coverage redundancy.

node i 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 $P_1 P_2 \dots P_{K-1} P_K = \prod_{i=1}^K P_i$ as our approximate expected delivery ratio for evaluation.

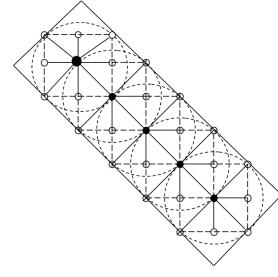


Fig. 4. An example of special node deployment.

Let us consider one special node deployment as illustrated in Fig. 4, where transmission radii values and packet reception probability values of all forward nodes are the same, that is, $P_1 = P_2 = \dots = P_K = P$, $R_1 = R_2 = \dots = R_K = R$. Then the expected broadcast delivery ratio $\bar{P} = P^K$ and Eq. (4) can be rewritten as

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

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 \bar{P} and at the same time minimize the total expected energy consumption \bar{E} . That is

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

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

Since there are several realistic physical layer models and they have different properties, the computation of p under different physical layer models is also different. In this paper we employ the widely used log-normal shadowing model. 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. Stojmenovic et al. [2] derive the approximation for p as a function of transmission radii r , reception distance d and packet length l which is shown

in Eq. (7)

$$p = \begin{cases} 1 - \frac{(d/r)^{q\beta}}{2} & 0 \leq d < r \\ \frac{(2r-d)^{q\beta}}{2} & r \leq d \leq 2r \\ 0 & \text{others,} \end{cases} \quad (7)$$

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%.

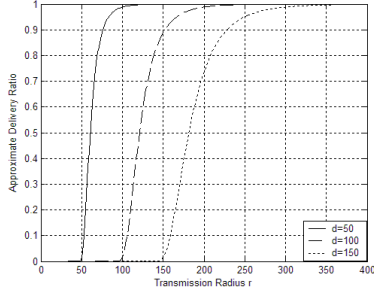


Fig. 5. A sample of approximate delivery ratio.

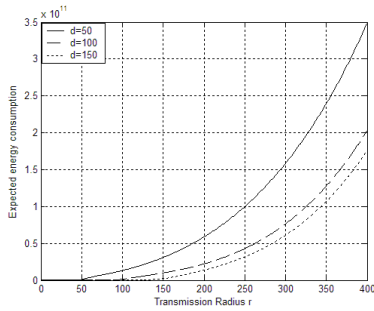


Fig. 6. A sample of total expected energy consumption.

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 loss of generality, we assume that 29 nodes ($N = 29$) with 4 consecutive forward nodes (including source node, then $K = 5$) are deployed in the network as shown in Fig. 4. By varying the network size we obtain three values for the distances between consecutive forward nodes ($d=50, 100$, and 150). Then we obtain \bar{P} and \bar{E} distributions for the above three scenarios as shown in Fig. 5 and 6. 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 radius* as the minimal radius 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 $P^K \leq \alpha = P^\eta \leq 1$ where η is defined as reception exponent and $0 \leq \eta \leq K$. When the coverage redundancy increases the value of η should decrease. 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 radii r and distance between nodes d , the computation of suitable transmission radius will be transferred to calculate the value of r when $p = \sqrt[\eta]{\alpha}$.

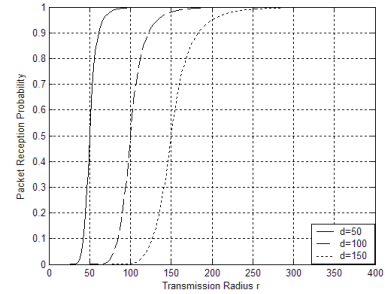


Fig. 7. A sample of packet reception probability.

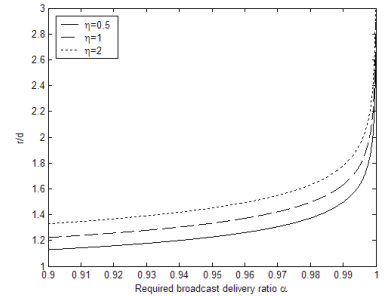


Fig. 8. Computed target coefficient based on α with $\beta = 4, q = 2$.

Fig. 7 shows a sample of the 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. Given that a high delivery ratio implies that $\alpha \geq 0.5$ and thus $p = \sqrt[\eta]{\alpha} \geq 0.5$, we 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 $r = [2(1 - \sqrt[\eta]{\alpha})]^{-1/q\beta} d$ as transmission radii. To extend our analysis result to general case, we define target coefficient as $\delta = r/d = [2(1 - \sqrt[\eta]{\alpha})]^{-1/q\beta}$ ($\delta > 1$) illustrated in Fig. 8. We can derive transmission radii according to target coefficient δ and different distances d between all relay nodes.

In short, rather than simply or randomly increasing the transmission radii we could choose a value for the radii by multiplying d with the target coefficient δ , which is derived according to the network-coverage requirement.

IV. REDUNDANT RADII BROADCAST PROTOCOLS

In the previous section, we proposed to increase the transmission radii used in broadcasting based on the distance d between relay nodes. Therefore, one should first determine the relay nodes and the values of d , which means computing the broadcast tree, and then the “target” radii should be obtained from all d and target coefficient δ for the actual data transmission. We call this the *Redundant Radii Scheme*.

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. Source node s has to manage two tables, $T(s)$ and $T'(s)$. The first one, $T(s)$, stores the neighbor link information based on maximum transmission radius R_m . The table $T'(s)$ also stores link information while it is based on smaller effective range R_e of R_m/δ . The broadcast tree calculation is based on $T'(s)$, and an ideal physical layer is assumed for this calculation (i.e., a link exists between two nodes u and v if and only if their distance is no more than transmission range r).

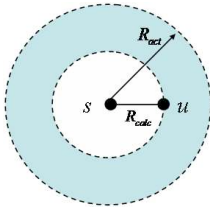


Fig. 9. Sketch map of redundant radius scheme.

As shown in Fig. 9, suppose R_{calc} represents the calculated transmission radii for node s (i.e., the distance d between s and its furthest 1-hop neighbor node), in the *redundant radii scheme* we should apply longer radii $R_{act} = \delta \times R_{calc}$ as the actual transmission radii. The idea of using 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 the physical-layer effects to validate the availability of logical links in the network.

V. PERFORMANCE EVALUATION

A. 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 II. Table III shows the parameters of the shadowing model. As our goal is to demonstrate the effectiveness of our scheme, we do not consider mobility in this paper. In mobile situations, we can apply a mobile management strategy to get updated location information, and then our protocols can still be utilized. In our simulations, the network is static with fixed size and nodes are always randomly placed. The number of nodes is variable to obtain different network

TABLE II
PARAMETERS FOR WIRELESS NODE MODEL.

Items	Value
frequency	2.4 GHz
maximum transmission range R_m	250 m
maximum transmit power	8.5872e-4 W
receiving power C_r	0.395 W
transmitting power C_e	0.660 W
MAC protocol	802.11
propagation model	shadowing

TABLE III
PARAMETERS FOR SHADOWING MODEL.

Items	Value
path loss exponent	4.0
Gaussian random variable	0 mean and standard deviation as 4.0 dB
seed for RNG	1
reference distance	1.0 m

density. The broadcast traffic rate is 1 packet per second with 64 bytes per packet. Each packet is issued from a randomly selected node.

As for the protocol to apply the *Redundant Radii Scheme*, we choose Broadcast Incremental Power (BIP) [13] since it is well known energy efficient protocol. 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.

B. Simulation Results

Firstly, we show the effectiveness of our proposed protocol on improving broadcast coverage. Fig. 10 (a) shows *BDR* comparison between our protocol (RR-BIP) and existing protocol (BIP). It is obvious that the *BDR* of our protocol is much higher than that of existing protocol. Despite of the network density the *BDR* of RR-BIP is almost larger than 90%. When δ reaches 1.5, the *BDR* value of RR-BIP is almost near 100%.

Next, we demonstrate the effectiveness of the target target/coefficient on achieving the required network coverage α . Since in our simulation $\beta = 4$ and $q = 2$, we get δ as $\delta = [2(1 - \sqrt{\alpha})]^{-1/8}$ where the value of reception exponent η is determined by practice measurement which is around 0.4 in relatively scarce networks ($N = 60$) and around 0.2 in relatively dense networks ($N = 90$). According to the required network coverage α we calculate the corresponding target

TABLE IV
BDR VALUE LIST FOR RR-BIP.

N	required η	calculate α	check δ	<i>BDR</i>	<i>BDR</i> - α
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

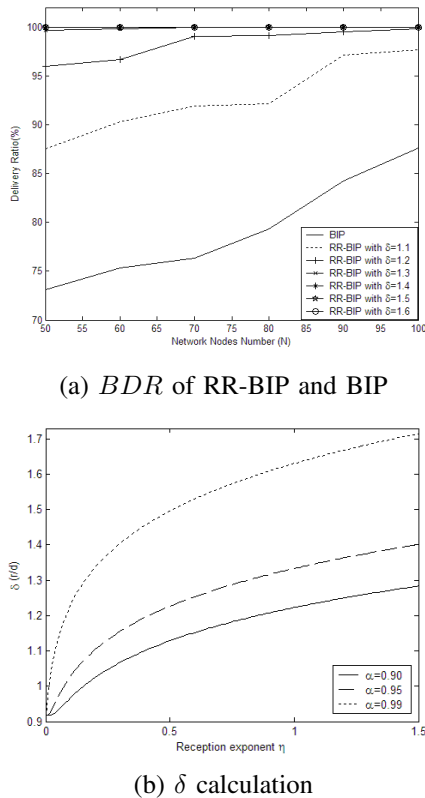


Fig. 10. *BDR* comparison between RR-BIP and BIP.

coefficient δ in Fig. 10 (b) and check the *BDR* value in Fig. 10 (a). We make lists in Table IV for convenient comparison. From Table IV we can see that by applying δ calculated from the proposed formula we can approximately achieve the required delivery ratio and the difference is limited within 0.022.

VI. 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 radii and proposed the “redundant radii” scheme. The experimental results we have presented illustrate the effectiveness of our scheme.

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