Impact of Practical Models on Power Aware Broadcast Protocols for Wireless Ad Hoc and Sensor Networks

Xu Hui, Manwoo Jeon, Shu Lei, Niu Yu, Jinsung Cho, and Sungyoung Lee[1]
Department of Computer Engineering, Kyung Hee University, Korea
{xuhui, imanoos, sl8132, niuyu}@oslab.khu.ac.kr, chojs@khu.ac.kr, sylee@oslab.khu.ac.kr

Abstract

The existing power aware broadcast protocols for wireless ad hoc and sensor networks assume the impractical model where two nodes can communicate if and only if they exist within their transmission radius. In this paper, we consider practical models for power aware broadcast protocols. First, we employ a universal and widely-used statistic shadowing model for physical layer where nodes can only indefinitely communicate near the edge of the communication range. Second, we consider two MAC layer model: EER (end-to-end retransmission) and HHR (hop-by-hop retransmission). Third, omni-antennas and directional antennas are dealt with separately. Next, we improve the reception probability function proposed in [7] and analyze how to choose the transmission radius between transmission nodes and relay nodes to get the trade-off between maximizing probability of delivery and minimizing energy consumption. From our analysis based on practical models, we have derived the optimal transmission range. The results presented in this paper are expected to improve the performance of power aware broadcast protocols in practical environments.

1. Introduction

Wireless ad hoc and sensor networks have emerged recently because of their potential applications in various situations such as battlefield, emergency rescue, and conference environments [1-4]. Ad hoc and sensor networks are without a fixed infrastructure; communications take place over a wireless channel, where each node has the ability to communicate with others in the neighborhood, determined by the transmission range. In such network, broadcast is a frequently required operation needed for route discovery, information dissemination, publishing services, data gathering, task distribution, alarming, time synchronization, and other operations. In a broadcasting task, a message is to be sent from one node to all the other ones in the network. Since ad hoc and sensor networks are power constrained, the most important design criterion is energy and computation conservation, broadcast is normally completed by multi-hop forwarding. There exist a lot of power aware broadcast protocols and their proposals are as following: first set up broadcast tree, and then at each transmission the transmission nodes will adjust their transmission radius to the distance between transmission nodes and relay nodes.

The existing power aware broadcast protocols for wireless ad hoc and sensor net-works assume the impractical model where two nodes can communicate if and only if they exist within their transmission radius. In this paper, we take practical models into consideration. For physical layer, we employ a universal and widely-used statistic shadowing model, where nodes can only indefinitely communicate near the edge of the communication range. For MAC layer, we consider two models: EER (end-to-end retransmission without acknowledgement) and HHR (hop-by-hop retransmission with acknowledgement). In addition, power aware broadcast protocols in networks with omni-antennas and networks with directional antennas are dealt with separately. Based on above practical models, we improve the reception probability function proposed in [7] and analyze how to choose the transmission radius between transmission nodes and relay nodes. We show how the practical physical layer and MAC layer impact the selection of transmission radius in power aware broadcast protocols and present the trade off between maximizing probability of delivery and minimizing energy consumption in the selection of transmission radius. From our analysis, we have derived the optimal transmission range. The results presented in this paper

[1] Dr. Jinsung Cho is the corresponding author.

are expected to improve the performance of power aware broadcast protocols in practical environments.

The remainder of the paper is organized as follows: Section 2 presents related work and offers some critical comments. In Section 3, we introduce our system model, including practical physical layer and MAC layer protocol model. In Section 4 we show the impact of practical physical layer on packet reception and energy consumption, and also present the improved approximation reception probability model and expected energy consumption. Section 5 presents the impact of practical models on power aware broadcast protocols focused on the selection of transmission radius. In Section 6, we present our conclusions and future work.

2. Related Work

In wireless ad hoc and sensor networks, the most important design criterion is energy and computation conservation since nodes have limited resources. Except reducing the number of needed emissions, radius adjustment is a good way to further reduce the energy consumption. For example, the well-known centralized algorithm is a greedy heuristics called BIP (Broadcast Incremental Power) [5]. It is a variant of the Prim's algorithm that takes advantage of the broadcast nature of wireless transmissions. Basically, 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.

Our work has been inspired by recent research work made in [6-9]. Mineo Takai, et al [6] focused on the effects of physical layer modeling on the performance evaluation of higher layer protocols, and have demonstrated the importance of the physical layer modeling even if 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. I. Stojmenovic, et al [7-9] presented guidelines on how to design routing and broadcasting in ad hoc and sensor networks taking physical layer impact into consideration. They apply the log normal shadow fading model to represent a realistic physical layer to 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 broadcasting in ad hoc network with realistic physical layer and propose new concept of dominating sets to be used in broadcasting process.

3. System Model

3.1. Physical Layer Model

Existing results in ad hoc wireless broadcasting are based on free-space or two-ray ground propagation models which represent the communication range as an ideal circle. In reality, the received power at certain distance is a random variable due to multi-path propagation effects, which is also known as fading effects. Therefore we take reality into consideration and employ shadowing model [10] as practical model which is expected to be more similar to reality.

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

$$\frac{P_r(d_0)}{\overline{P_r(d)}} = (\frac{d}{d_0})^{\beta} \tag{1}$$

β is called the path loss exponent and is usually empirically determined by field measurement; $\beta = 2$ is for free space propagation. Larger values of β correspond to more obstructions and hence faster decrease in average received power as distance becomes larger. $P_r(d_0)$ can be computed from free space model. The path loss is usually measured in dB. So from Eq. (1) we have

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

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

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

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}. σ_{dB} is called the shadowing deviation, and is also obtained by measurement. Eq. (3) is also known as a log-normal shadowing model.

The shadowing model extends the ideal circle model to a richer statistical model; nodes can only probabilistically communicate near the edge of the communication range.

3.2. MAC Layer Protocol Model

In this section, we introduce two kinds of MAC layer protocols: HHR (hop-by-hop retransmission) protocol where the sender of a packet requires an acknowledgement from receiver and EER (end-to-end retransmission) protocol where the sender of a packet does not.

In EER case, the sender sends an packet and the receiver may or may not receive the packet which depends on the reception probability. For HHR case, we employ a MAC layer communication protocol between two nodes proposed in [7-9]. After receiving any packet from sender, the receiver sends u acknowledgements. If the sender does not receive any acknowledgement, it will retransmit the packet. They also derive the expected number of messages in this protocol as measure of hop count between two nodes. The count includes transmissions by sender and acknowledgments by receiver. They assume both the acknowledgement and data packets are of the same length.

Let S and A be the sender and receiver nodes respectively, and let $|SA| = d$ be the distance between them. Probability that A receives the packet from S is $p(d)$. Probability that S receives one particular packet from A is $p(d)$ and the probability that it does not receive the packet is 1- $p(d)$. Therefore, the probability that S does not receive any of the u acknowledgements is $(1-p(d))^u$. Thus, the probability that S receives at least one of u acknowledgements from A is $1-(1-p(d))^u$. Therefore, $p(d)(1-(1-p(d))^u)$ is the probability that S receives acknowledgement after sending a packet and therefore stops transmitting further packets. Thus, the expected number of packets at S is $1/[p(d)(1-(1-p(d))^u)]$. Each of these packets is received at A with probability $p(d)$. If received correctly, it generates u acknowledgements. The total expected number of acknowledgements sent by A is then $up(d)/[p(d)(1-(1-p(d))^u)] = u/[(1-(1-p(d))^u)]$. The total expected hop count between two nodes at distance d is then $1/[p(d)(1-(1-p(d))^u)]+u/[(1-(1-p(d))^u)]$.

4. Impact of Practical Models on Packet Reception and Energy Consumption

4.1. Reception Probability Model

In shadowing model, nodes can only probabilistically communicate near the edge of the communication range. I. Stojmenovic, et al [7-9] derives the approximation for probability of receiving a packet successfully as a function of distance d between two nodes. The model is having in mind packet length L = 120 and an error within 4% $p(r,d)=(1-(d/r)^{2\beta}/2)$ for $d<r$ and $((2r-d)/r)^{2\beta}/2$ for all other d, where β is the power attenuation factor, with fixed value between 2 and 6, r is transmission radius with $p(r, d=r)$ = 0.5 and $d<2r$.

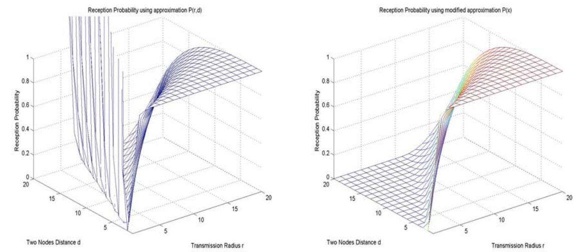


Fig.1. Reception probability with approximation and modified approximation $p(r, d)$

Fig. 1(a) shows the reception probability with approximation $p(r, d)$ when β is 2. From Fig. 1(a), we can see there are some error results since probability value cannot be larger than 1. The following shows our precise analysis:

$$p(r,d)=\begin{cases} 1-\dfrac{(\frac{d}{r})^{2\beta}}{2} & 0\le d<r \\ \dfrac{(\frac{2r-d}{r})^{2\beta}}{2} & d\ge r \end{cases} \xrightarrow{0\le p\le 1} \begin{cases} 0\le 1-\dfrac{(\frac{d}{r})^{2\beta}}{2}\le 1 & (0\le d<r) \\ 0\le \dfrac{(\frac{2r-d}{r})^{2\beta}}{2}\le 1 & (d\ge r) \end{cases}$$

$$\begin{cases} 0\le d\le 2^{\frac{1}{2\beta}}r & (0\le d<r) \\ (2-2^{\frac{1}{2\beta}})r\le d\le (2+2^{\frac{1}{2\beta}})r & (d\ge r) \end{cases} \Rightarrow \begin{cases} 0\le d<r \\ r\le d\le (2+2^{\frac{1}{2\beta}})r \end{cases}$$

While when d increases to $2r$, the probability has been zero which means the distance between two nodes has been too far, therefore d should be less than $2r$. At last, the modified probability model is

$$p(r,d)=\begin{cases} 1-\dfrac{(\frac{d}{r})^{2\beta}}{2} & 0\le d<r \\ \dfrac{(\frac{2r-d}{r})^{2\beta}}{2} & r\le d\le 2r \\ 0 & others \end{cases}$$

The figure of our modified approximation $p(r, d)$ when β is 2 is shown in Fig. 1(b).

4.2. Expected Energy Consumption

Assume now that two nodes are at distance d, but a packet is sent with transmission radius r; let E represent energy for processing signals at both transmitter and receiver nodes. The exact transmission power is then r^β multiplied by a constant, which is assumed to be 1 for simplicity. Therefore the energy needed by sending node is $E+r^\beta$, while energy at receiving node is E, for a combined energy $2E+r^\beta$. The reception probability at distance d is $p(d)$= $p(rd/r)$ = $g(d/r)$, where we defined $g(y) = p(r\,y)$.

In EER case, the sender sends a packet and the receiver may or may not receive the packet, which depends on the probability of receiving. Therefore, the expected energy consumption is $(2E+r^{\beta})g(d/r) = (2E+d^{\beta}(r/d)^{\beta})g(d/r)$.

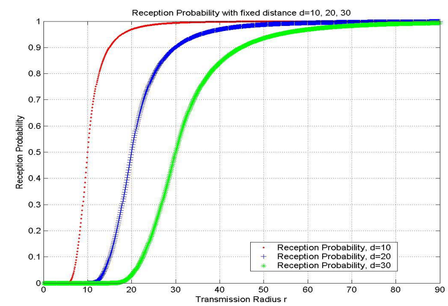
In HHR case, a message is retransmitted between two nodes until it is received and acknowledged correctly; after receiving any packet from the sender, the receiver sends u acknowledgements. Transmissions and acknowledgements in general do not need to be done with the same transmission powers. However, since they use the same probability function, we can argue that the optimal power is achieved when both of them use the same power. Then, because the expected number of transmitted packets (for u = 1) is $1/g^2(d/r)$ and the expected number of acknowledgements is $1/g(d/r)$, the total expected energy consumption is $(2E+r^{\beta})(1/g(d/r)+1/g^2(d/r))$, which is a function of one variable that needs to be optimized for r as function of d. The formula is as following $(2E+d^{\beta}(r/d)^{\beta})(1/g(d/r)+1/g^2(d/r))$.

5. Impact of Practical Models on Power Aware Broadcast Protocols

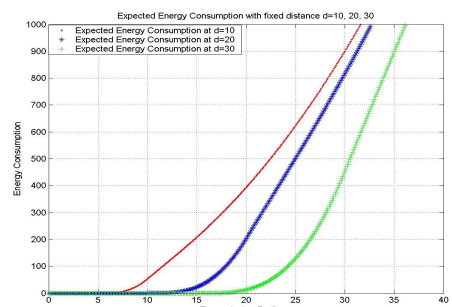
For broadcast with practical models, first we set up broadcast tree using power aware broadcast protocols under impractical model; and then, choose the optimal transmission radius for every retransmission. As for the metric to decide the optimal transmission radius, there exists a trade-off or negotiation between maximizing probability of delivery and minimizing energy consumption. We propose the following rules: for broadcasting in wireless network with omni-antennas, minimizing energy consumption is the primary metric; otherwise, for network with directional antennas, maximizing probability of delivery will be the primary metric, since transmission coverage overlapping is much fewer than that in networks with omni-antennas.

5.1. EER Case

In EER case, a sender sends a packet and a receiver may or may not receive the packet which depends on the reception probability. The reception probability function is $p(r,d)=(1-(d/r)^{2\beta}/2)$ for $d<r$, $((2r-d)/r)^{2\beta}/2$ for $r<d<2r$, and 0 for all the other d. For network with directional antennas, since maximizing probability of delivery is our primary metric, at least we have to guarantee the reception probability no less than 0.5; however if the reception probability is near 1, the energy consumption will be too high. Therefore, we choose [0.5 0.9] as the acceptable reception probability scope. From Fig. 1 we can find that if $r>d$, the scope of reception probability is [0.5, 1]; otherwise, if $r<d$, reception probability will be less than 0.5. Since we should guarantee the reception probability no less than 0.5, we will only use $p(r,d)=(1-(d/r)^{2\beta}/2)$ for $d<r$. For any value of β, $2\le\beta\le 6$, if we want to get the relationship of d and r ($r>d$) for certain reception probability α, we can set up the formula as $1-(d/r)^{2\beta}/2=\alpha$, then we get $r=[2(1-\alpha)]^{-1/2\beta}d$. Therefore, in order for reception probability to be [0.5 0.9], the transmission radius should be [d $(1/5)^{-1/2\beta}d$]. We can verify it through Fig. 2, where β=2, d=10, 20 and 30. According to our proposal, we can choose the transmission radius in the scope of [10 15], [20 30] and [30 45] respectively. In Fig. 2(a), the according reception probability is in the scope of [0.5 0.9]; in Fig. 2(b), the according expected energy consumption is in the scope of [53 208], [203 817] and [453 1830] respectively.



(a) Reception probability



(b) Expected energy consumption

Fig. 2. Reception probability and expected energy consumption with fixed distance d

For network with omni-antennas, minimizing expected energy consumption is primary metric. We know as transmission r increases, the expected energy consumption will also increase. Therefore, we want to choose the transmission radius r value as small as possible. Whereas, even minimizing energy consumption is the primary metric, we still cannot neglect the reception probability. According our proposal above, which is selecting r in the scope [d $(1/5)^{-1/2\beta}d$], and getting the reception probability scope [0.5 0.9], by guaranteeing reception probability not less than 50%, we decide to choose d as the transmission radius r.

5.2. HHR Case

In HHR case, a message is retransmitted between two nodes until it is received and acknowledged correctly; after receiving any packet from sender, the receiver sends u acknowledgements. Considering the characteristic of MAC layer in HHR case, it's better to be employed in networks with directional antennas, which represent one to one transmission model. In addition, we can find the MAC layer has already guaranteed successful reception, therefore our research moves to minimizing the expected hop number and expected energy consumption between two nodes.

According to the MAC layer protocol in HHR case, $p(d)(1-(1-p(d))^u)$ is the probability that sender S receives acknowledgement after sending a packet and therefore stops transmitting further packets. Each of these packets is received at A with probability $p(d)$. When u equals 1, reception probability at sender S and receiver A is respectively $p^2(d)$ and $p(d)$, that is $g^2(d/r)$ and $g(d/r)$. Since the expected packets number is respectively $1/g^2(d/r)$ and $1/g(d/r)$, our work is transferred to maximize the reception probability at sender S and receiver A.

For any value of β, $2 \le \beta \le 6$, for receiver A, the relationship of d and r (r>d) for certain reception probability α is $r = [2(1-\alpha)]^{-1/2\beta} d$, then in order for reception probability to be [0.5 0.9], the transmission radius should be $[d \ \ (1/5)^{-1/2\beta} d]$; however, for sender S, the relationship of d and r (r>d) for certain reception probability α is $r = [2(1-\alpha^{1/2})]^{-1/2\beta} d$, then in order for reception probability to be [0.5 0.9], the transmission radius should be $[[2(1-(0.5)^{1/2})]^{-1/2\beta} d \ \ [2(1-(0.9)^{1/2})]^{-1/2\beta} d]$. Therefore considering the reception probability of both sender S and receiver A, our proposal can be extended as the following: in HHR case, we choose r from the scope of $[[2(1-(0.5)^{1/2})]^{-1/2\beta} d \ \ (1/5)^{-1/2\beta} d]$, where for sender S the scope of reception probability is [0.5 0.9) and for receiver A the scope of reception probability is within (0.5 0.9]. We can verify it through Fig. 3, where β=2, d=10, 20 and 30. The reception probability at sender S and at receiver A with fixed distance d when β is 2 is showed in Figure 3.

According to our proposal, we can choose the transmission radius in the scope of [11.4, 15], [22.9 30] and [34.3 45] respectively. In Fig. 3, for sender S, the scope of reception probability is [0.5 0.8] and for receiver A, the scope of reception probability is within [0.7 0.9].

In HHR case, because of the characteristic of MAC layer, the number of transmission between two nodes is more than one, therefore expected hop count and expected energy consumption will be higher than that in EER case. Fig. 4 shows the total expected hop count and energy consumption including sender S and receiver A when β is 2.

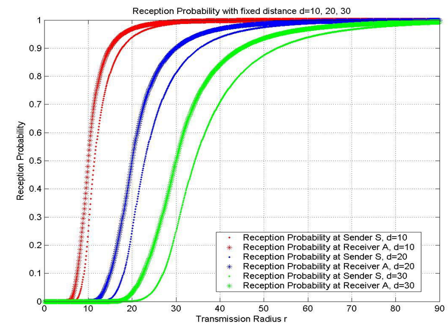
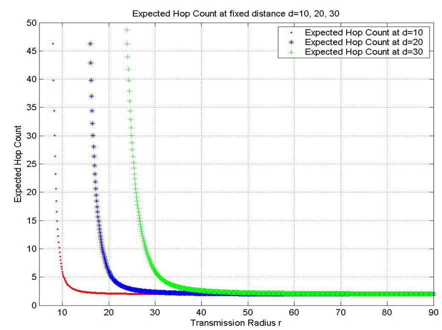
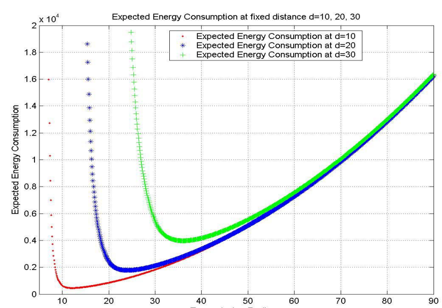


Fig. 3. Reception probability at sender S with fixed distance d=10, 20, 30



(a) Total expected hop count



(b) Total expected energy consumption

Fig. 4. Total expected hop count and energy consumption with fixed distance d

We can verify whether our proposal of choosing r from the scope of $[[2(1-(0.5)^{1/2})]^{-1/2\beta} d \ \ (1/5)^{-1/2\beta} d]$ is reasonable or not. The total expected hop count and energy consumption with fixed distance d=10, 20, 30 when β is 2 is showed in Figure 4. According to our proposal, we can choose the transmission radius in the scope of [11.4 15], [22.9 30] and [34.3 45] respectively. Fig. 4(a) shows that if the transmission radius r is not less than the distance 10, 20 and 30 respectively, expected hop count will be less than 5 and also at last decrease to a constant number. Fig. 4(b) shows that the expected energy consumption can get minimum value when r is around 11.4, 22.9 and 34.3 respectively; whereas if r is larger than those values, the expected energy consumption will increase. Therefore, even if r is larger than 15, 30 and 45 respectively, we can get the minimum expected hop count, but because the expected energy consumption will be larger, so we still cannot choose r larger than 15, 30 and 45 respectively. In a word, our proposal for HHR case is to choose the transmission radius r in the scope of $[[2(1-(0.5)^{1/2})]^{-1/2\beta}d \;\; (1/5)^{-1/2\beta}d]$, which can get optimal performance at expected hop count and energy consumption.

9. Conclusions

To the best of our knowledge, this is the first work that considers the impact of practical physical layer and MAC layer model on power aware broadcast protocols. We investigated power aware broadcast protocols with and without acknowledgements and presented the trade off between maximizing probability of delivery and minimizing energy consumption for ad hoc wireless networks with practical models. We show how the practical physical layer and MAC layer impact the selection of transmission radius in power aware broadcast protocols. In EER case, for network with omni-antennas, minimizing energy consumption is the primary metric, and by guaranteeing reception probability no less than 50%, we decide to choose the distance d as transmission radius, where d is the distance between transmission node and relay node; in network with directional antenna, we propose to choose the transmission radius in the scope of $[d \;\; (1/5)^{-1/2\beta}d]$ to maximize the probability of delivery. In HHR case, the MAC layer protocol is not suitable to one-to-all communication; therefore we only consider networks with directional antennas. Since the MAC layer has already guaranteed successful reception, our research moves to minimize the expected hop number and expected energy consumption between two nodes. For networks with directional antennas we propose to choose the transmission radius in the scope of $[[2(1-(0.5)^{1/2})]^{-1/2\beta}d \;\; (1/5)^{-1/2\beta}d]$, which can get optimal performance at expected hop count and energy consumption.Currently, we are designing new power aware broadcast protocols based on our analysis.

Acknowledgement

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