A Probabilistic Neighbor Discovery Algorithm in Wireless Ad hoc Networks

Taewon Song*, Hyunhee Park†, and Sangheon Pack*
*School of Electrical and Engineering
Korea University, Seoul, Korea
Email: {crazytb,shpack}@korea.ac.kr
†French Institute for Research in Computer Science and Control
INRIA, Rennes, France
Email: hyunhee.park@inria.fr

***Abstract*—In wireless ad hoc networks, it is difficult to share the information on neighbor devices in a distributed manner. Therefore, efficient neighbor discovery algorithms should be devised for self-organization in wireless ad hoc networks. In this paper, we propose a probabilistic neighbor discovery (PND) algorithm, which aims at reducing the neighbor discovery time by adjusting the transmission probability of advertisement messages through the muiltiplicative-increase/multiplicative-decrease (MIMD) policy. To further improve PND, we consider the collision detection (CD) capability in which a device can distinguish between successful reception and collision of advertisement messages. Simulation results show that the transmission probabilities of PND and PND with CD converge on the optimal value quickly although the number of devices is unknown. As a result, PND and PND with CD can reduce the neighbor discovery time by 15.6% and 57.0%, respectively, compared with the ALOHA-like neighbor discovery algorithm.**

***Index Terms*—Collision detection, distributed MAC, neighbor discovery, wireless ad hoc networks.**

I. Introduction

Neighbor discovery is an essential procedure to initialize wireless ad hoc networks and to let devices know one-hop neighbor information. Moreover, neighbor discovery is a vital part to design routing algorithm, topology control, and medium access control (MAC). Nevertheless, a design of efficient neighbor discovery algorithms is challenging since it is difficult to share the information on neighbor devices in a distributed manner in wireless ad-hoc networks.

In conventional neighbor discovery algorithms, a device broadcasts an advertisement message including the device information by an ALOHA-like protocol. Specifically, each device transmits an advertisement message with probability p and retains receiving state with probability $1 - p$. Therefore, how to choose the transmission probability p is a key design issue in neighbor discovery algorithms. To address this issue, a number of studies have been conducted in the literature [1], [2], [3]. Most of them, however, assume that the network size in terms of the number of devices is known to all devices in advance. Definitely, this is an unreasonable assumption since it is difficult to know the network size in dynamic wireless ad-hoc networks. Recently, Vasudevan *et al.* [4] relaxed the network size assumption and proposed a neighbor discovery algorithm reducing the transmission probability in a geometrical manner. However, this algorithm is not adaptive to the transmission results of advertisement messages and thus the optimal performance cannot be attained.

In this paper, we propose a probabilistic neighbor discovery (PND) algorithm, which aims at reducing the neighbor discovery time when the number of devices is unknown. A device decides its transmission probability according to transmission results of advertisement messages: reception, collision, and idle. With an adaptive adjustment depending on the transmission results, the transmission probabilities can converge on the optimal value quickly.

To further improve the performance of PND, we also investigate the collision detection (CD) capability [5], [6], [7]. When the CD capability is enabled, a transmitting device can be aware of the transmission result of its advertisement message. Once a successful transmission is detected, the device can complete its neighbor discovery procedure. Therefore, the number of devices involved in the neighbor discovery procedure decreases as the time goes, which reduces the total neighbor discovery time. Extensive simulation results demonstrate that PND and PND with CD can reduce the neighbor discovery time by 15.6% and 57.0%, respectively, compared to the ALOHA-like neighbor discovery algorithm [1].

The rest of the paper is organized as follows. In Section II, the system model for PND is described. The PND algorithm is described in Section III and the impact of collision detection is analyzed in Section IV. Section V presents simulation results and Section VI concludes this paper.

II. System Model

In this work, we assume the use of slotted ALOHA protocol for medium access control. In the slotted ALOHA protocol, time is slotted and a device can transmit an advertisement message only at the beginning of a time slot. We also assume that the slotted ALOHA protocol operates in a half-duplex environment. That is, a device cannot receive any message while transmitting a message. When two or more messages are transmitted at the same time slot, a collision event occurs. Typically, the collision cannot be detected by the transmitting device in wireless environments. However, as in [7], the collision can be detected with the PHY-layer information

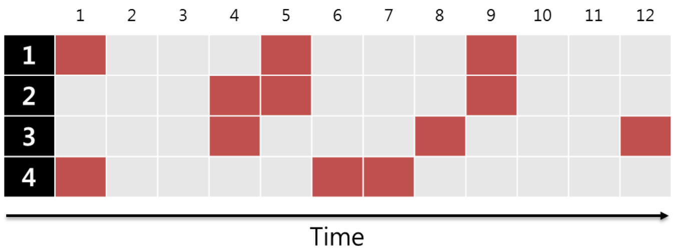


Fig. 1. Example of slotted ALOHA-like neighbor discovery.

or another radio channel. Since such a collision detection capability can improve the performance of neighbor discovery, we consider both the cases with and without the collision detection capability. Devices are statically located and have unique identifiers. The value of the transmission probability is included in the advertisement message. Therefore, when a device receives an advertisement message, the device can update its transmission probability adaptively.

Figure 1 shows a basic operation of the slotted ALOHA-like neighbor discovery process. Let D be a set of devices in the network. In addition, $D_T(t)$ is a set of devices transmitting advertisement messages in the time slot t whereas $D_W(t)$ is a set of devices waiting for the reception of advertisement messages in the time slot t. In Figure 1, colored box stands for the transmission of an advertisement message. For example, devices 1 and 4 transmit advertisement messages at the first time slot whereas no advertisement messages are transmitted at the second time slot. Therefore we have $D_T(1) = \{1, 4\}$, $D_W(1) = \{2, 3\}$, $D_T(2) = \emptyset$, and $D_W(2) = \{1, 2, 3, 4\}$.

III. Probabilistic Neighbor Discovery

In this section, we first describe the operation of PND. After that, an illustrative example for PND is presented.

A. PND Operation

PND can be implemented in a distributed manner. In other words, each device computes its transmission probability for an advertisement message autonomously and broadcasts the probability by means of the slotted ALOHA-like protocol. Let $p_{t,i}$ be the transmission probability of device i in the time slot t. Then, in the time slot t, device i transmits its advertisement message with probability $p_{t,i}$ whereas listens to any advertisement messages with probability $1 - p_{t,i}$. Device i updates its transmission probability in the time slot $t+1$, denoted by $p_{t+1,i}$, based on the multiplicative increase and multiplicative decrease (MIMD) policy. That is, $p_{t+1,i}$ multiplicatively increases or decreases depending on the value of the received transmission probability in the time slot t. To compute $p_{t+1,i}$, we need to consider four cases: 1) device i transmits an advertisement message in the time slot t, 2) device i does not transmit any advertisement message and receives an advertisement message without any collision, 3) device i does not transmit any advertisement message and receives a collided advertisement message, and 4) no devices transmit any advertisement messages.

1) Case 1: When device i transmits an advertisement message in the time slot t, device i cannot receive any advertisement messages from neighbors due to the half-duplex operation. Therefore, the transmission probability is not changed in the time slot $t+1$. That is, $p_{t+1,i}$ is updated as

$$\underset{\forall i \in D_T(t)}{p_{t+1,i}} = p_{t,i}. \tag{1}$$

2) Case 2: Device i waits for an advertisement message in the time slot t with probability $1 - p_{t,i}$. Assume that only device j transmits an advertisement message in the time slot t with probability $p_{t,j}$ (i.e., $|D_T(t)| = 1$) and the advertisement message is received by device i. Then, the transmission probability of device i in the time slot $t+1$ is computed as

$$\underset{\forall i \in D_W(t)}{p_{t+1,i}} = p_{t,j}. \tag{2}$$

3) Case 3: When two or more devices transmit advertisement messages (i.e., $|D_T(t)| \geq 2$), the advertisement messages are collided. Then, devices in $D_W(t)$ can receive collided messages, which indicates that the transmission probabilities of devices are overestimated, the transmission probability should be reduced. Therefore, by multiplicative decrease, devices in $D_W(t)$ calculate their transmission probabilities in the time slot $t+1$ as

$$\underset{\forall i \in D_W(t)}{p_{t+1,i}} = \frac{p_{t,i}}{c_{coll}} \tag{3}$$

where c_{coll} (> 1) is a parameter for multiplicative decrease.

4) Case 4: If no advertisement messages are transmitted in the time slot t (i.e., $|D_T(t)| = 0$), the time slot is idle. Since no messages are received, all devices in $D_W(t)$ consider that the transmission probabilities are underestimated. Hence, the transmission probabilities should be increased. That is, $p_{t+1,i}$ is given by

$$\underset{\forall i \in D_W(t)}{p_{t+1,i}} = p_{t,i} \cdot c_{idle} \tag{4}$$

where c_{idle} (> 1) is a parameter for multiplicative increase.

B. Example of PND

Table I shows an example of PND in a slotted ALOHA environment where four devices (i.e., 1, 2, 3, and 4) are represented in the first column. A gray box in ‘tx’ column represents that the corresponding device transmits an advertisement message in the time slot. $p_{0,i}$ denotes the initial transmission probability of device i. Initial transmission probabilities of devices 1, 2, 3, and 4 are set to 0.4, 0.3, 0.2 and 0.1, respectively. Both c_{coll} and c_{idle} are set to 1.5. These values are chosen for the purpose of convenient description.

At the first time slot, device 3 successfully transmits an advertisement message including its identification (ID) and transmission probability of $p_{0,3}$. After that, devices 1, 2 and 4 receive the advertisement message from device 3, and thus we have $D_T(1) = \{3\}$ and $D_W(1) = \{1, 2, 4\}$. Devices belonging

TABLE I
AN EXAMPLE OF PND OPERATION.

Device	$p_{0,i}$	1st timeslot		2nd timeslot		3rd timeslot		4th timeslot	
		tx	$p_{1,i}$	tx	$p_{2,i}$	tx	$p_{3,i}$	tx	$p_{4,i}$
1	0.4		0.2		0.3		0.2		0.3
2	0.3		0.2		0.3		0.3		0.3
3	0.2		0.2		0.3		0.3		0.3
4	0.1		0.2		0.3		0.2		0.3

TABLE II
AN EXAMPLE OF PND WITH CD OPERATION.

Device	$p_{0,i}$	1st timeslot		2nd timeslot		3rd timeslot		4th timeslot	
		tx	$p_{1,i}$	tx	$p_{2,i}$	tx	$p_{3,i}$	tx	$p_{4,i}$
1	0.4		0.2		0.13		0.2		0.2
2	0.3		0.2		0.13		0.2		
3	0.2								
4	0.1		0.2		0.13		0.2		0.2

to $D_W(1)$ update their transmission probabilities based on the received transmission probability as described in Section III-A. As a result, the transmission probabilities of devices 1, 2, 3, and 4 are given by $p_{1,1} = 0.2$, $p_{1,2} = 0.2$, $p_{1,3} = 0.2$, and $p_{1,4} = 0.2$, respectively.

In the second time slot, no advertisement messages are transmitted and thus the transmission probability is multiplicatively incremented by c_{idle}. Since we have $D_T(2) = \emptyset$ and $D_W(2) = \{1, 2, 3, 4\}$, the transmission probabilities of devices 1, 2, 3, and 4 are given by $p_{2,1} = 0.2 * 1.5 = 0.3$, $p_{2,2} = 0.2 * 1.5 = 0.3$, $p_{2,3} = 0.2 * 1.5 = 0.3$, and $p_{2,4} = 0.2 * 1.5 = 0.3$, respectively.

Advertisement messages from devices 2 and 3 in the third time slot are collided (i.e., $D_T(3) = \{2, 3\}$ and $D_W(3) = \{1, 4\}$), and then devices 1 and 4 detect the collided message. Since transmitting devices 2 and 3 cannot detect the collision event, they should retain their transmission probabilities and we have $p_{3,2} = 0.3$ and $p_{3,3} = 0.3$. On the other hand, devices 1 and 4 receive collided advertisement messages and thus reduce their transmission probabilities by c_{coll} , i.e., $p_{3,1} = 0.3/1.5 = 0.2$ and $p_{3,4} = 0.3/1.5 = 0.2$.

In the last fourth time slot, only device 2 transmits an advertisement message, i.e., $D_T(4) = \{2\}$ and $D_W(4) = \{1, 3, 4\}$. Therefore, the transmission probability of device 2 is not changed, i.e., $p_{4,2} = 0.3$. On the other hand, devices 1, 3 and 4 use the transmission probability advertised by device 2 and thus we have $p_{4,1} = 0.3$, $p_{4,3} = 0.3$, and $p_{4,4} = 0.3$.

IV. PND WITH COLLISION DETECTION CAPABILITY

In PND without collision detection capability, a transmitting device does not have any information on its transmission result. Therefore, even after a successful transmission, the device should be involved in the neighbor discovery procedure. In addition, the neighbor discovery procedure is terminated only when all advertisement messages from devices in D are successfully transmitted.

On the other hand, by means of the collision detection capability, a transmitting device can be aware of whether a transmitted message is successfully transmitted or collided. Therefore, if a device broadcasts its advertisement message successfully, the devices does not participate in the neighbor discovery procedure any more. As a result, the completion time of neighbor discovery can be reduced.

Table II shows an example of PND with CD where initial transmission probabilities of devices 1, 2, 3, and 4 are set to 0.4, 0.3, 0.2 and 0.1, respectively, and both c_{coll} and c_{idle} are set to 1.5.

At the first time slot, device 3 transmits an advertisement message (i.e., $D_T(1) = \{3\}$ and $D_W(1) = \{1, 2, 4\}$). By using the collision detection capability, device 3 knows that its transmission is successful and thus it is not involved in the neighbor discovery procedure any more.

In the second time slot, devices 1 and 2 transmit advertisement messages and the messages are collided (i.e. $D_T(2) = \{1, 2\}$ and $D_W(2) = \{4\}$). Since devices 1 and 2 can detect the collision event in PND with CD and device 4 receives a collided message, transmission probabilities of devices 1, 2, and 4 are set to $0.2/1.5 \simeq 0.13$, i.e., $p_{2,1} = p_{2,2} = p_{2,4} = 0.13$.

On the other hand, no advertisement messages are transmitted in third time slot (i.e. $D_T(3) = \emptyset$ and $D_W(3) = \{1, 2, 4\}$). Hence the transmission probabilities are multiplicatively increased by c_{idle}, and we have $p_{3,1} = p_{3,2} = p_{3,4} = 0.2/1.5 * 1.5 = 0.2$.

In the fourth time slot, only device 2 transmits an advertisement message, i.e., $D_T(4) = \{2\}$ and $D_W(4) = \{1, 4\}$. Therefore, the transmission is successful and device 2 terminates its neighbor discovery procedure.

V. SIMULATION RESULTS

To evaluate the performance of PND and PND with CD, we implemented a simulator using MATLAB. A neighbor discovery procedure is terminated when advertisement messages from all devices are transmitted, and simulation results from 1000 neighbor discovery procedures are averaged for credible simulation results. The initial transmission probability is randomly set to a value between 0 and 0.5. We compare the performance of PND with 1) the optimal algorithm where the number of devices, N, is given and the transmission probability is set to $1/N$ and 2) the ALOHA-like neighbor discovery (AND) algorithm [1]. In AND, the neighbor discovery procedure proceeds in phases and each phase consists of one or more time slots. Devices geometrically reduce their transmission probabilities until they enter the next phase. Specifically, a device in phase i transmits an advertisement message with the probability of $1/2^i$ and phase i lasts for $2^i e(\ln 2^i + c)$ time slots, which is mathematically derived in [1] and c is an approximation error (typically set to 0).

A. Effect of Initial Transmission Probability

Figure 2 shows the neighbor discovery time when randomized and optimal initial transmission probabilities are adopted. It can be found that there is no significant difference between two cases. This is because the transmission probability can converge on the optimal value quickly when PND and PND

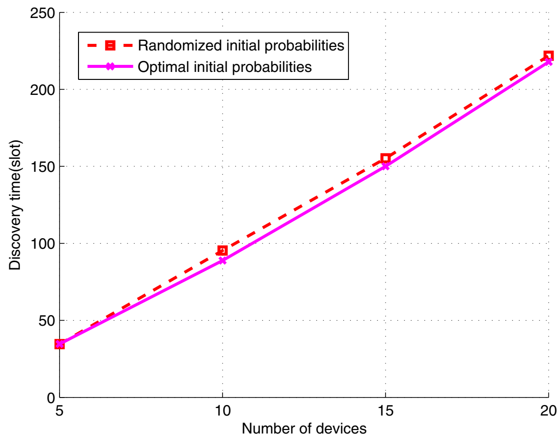


Fig. 2. Neighbor discovery time: randomized vs optimal initial probabilities.

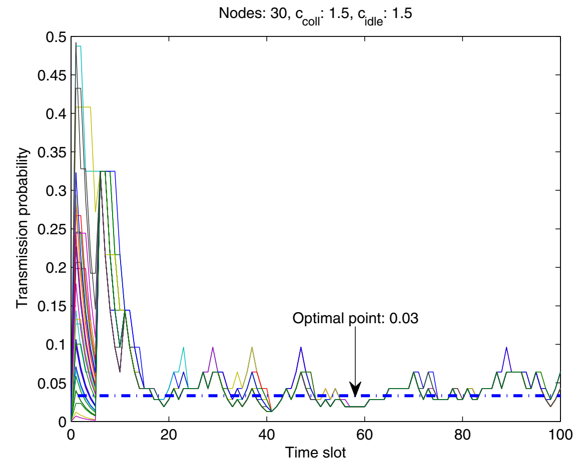
with CD are used, which will be elaborated in the next subsection.

B. Convergence of Transmission Probability

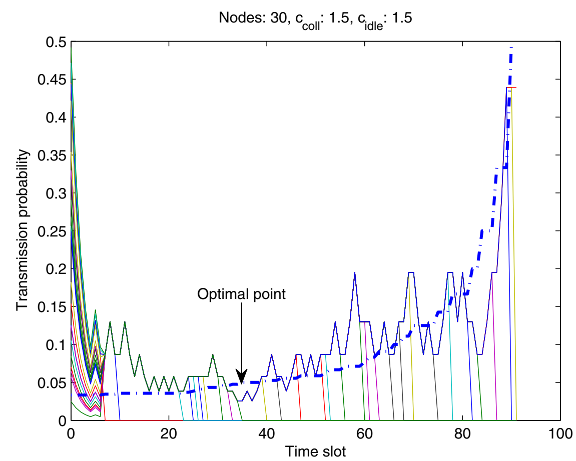
PND iterates the neighbor discovery procedure described in Section III-A until all advertisement messages are successfully transmitted. Figure 3 shows the computed transmission probabilities of 30 devices for 100 time slots. The optimal value line of Figure 3(b) shapes like a quadratic function since devices that completed the transmissions of their advertisement messages do not participate in the neighbor discovery procedure any more. From Figure 3(a), it can be seen that the transmission probabilities converge on the optimal transmission probability (i.e., $1/30 \simeq 0.03$). Figure 3(b) shows the computed transmission probabilities when the collision detection capability is enabled. Similar to Section III-A, the computed probabilities are reduced to the initial optimal transmission probability (i.e., 0.03). Meanwhile, it can be found that the transmission probabilities increase as more time slots are elapsed. This can be explained as follows. As mentioned earlier, in PND with collision detection capability, a device that transmitted its advertisement message successfully does not participate in the neighbor discovery procedure no longer. Therefore, the optimal transmission probability is increased after excluding the completed devices, and the computed transmission probabilities converge to the increased optimal probability.

C. PND vs. AND

Figure 4 compares the neighbor discovery time of PND and AND without CD where PND(X, Y) represents PND with $c_{coll} = X$ and $c_{idle} = Y$. It can be found that PND(1.5, 1.5) outperforms AND in terms of discovery time by 3.1% and 15.6% when N is 10 and 40, respectively. PND(1.5, 1.5) also shows comparable performance to the optimal algorithm. Discovery time of PND(1.5, 1.5) is no more than discovery time of optimal algotithm by 9.1% when N is 40. Meanwhile, PND(1.1, 1.5) and PND(1.5, 2)



(a) Transmission probabilities of PND.

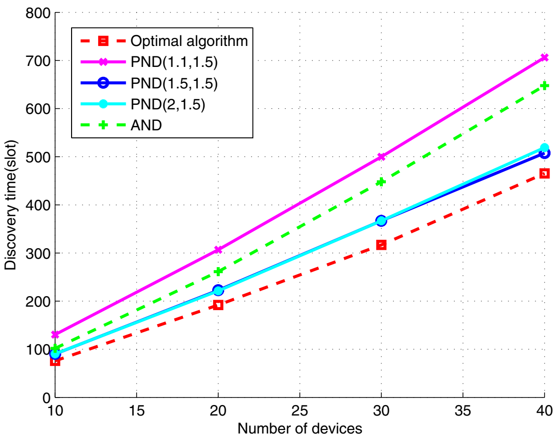


(b) Transmission probabilities of PND with CD.

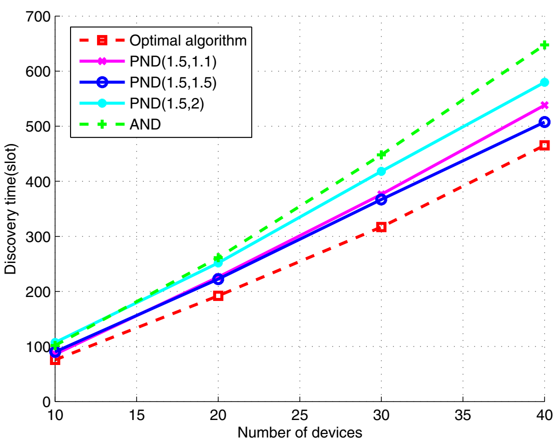
Fig. 3. Transmission probabilities in PND and PND with CD (Number of devices: 30, $c_{coll} = 1.5$, $c_{idle} = 1.5$).

show the increased neighbor discovery time compared with PND(1.5, 1.5) whereas PND(1.1, 1.5) and PND(1.5, 2) exhibit shorter neighbor discovery time than AND. In short, although the performance of PND is affected by the values of c_{coll} and c_{idle}, PND can provide better performance than AND.

Fig. 5 shows the neighbor discovery time of PND with CD. It can be seen that PND(1.5, 1.5) with CD can reduce the neighbor discovery time of AND with CD by 45.7% and 57.0% when N is 10 and 40, respectively. In addition, when we compare Figures 4 and 5, it can be found that PND(1.5, 1.5) with CD can improve the neighbor discovery time of PND(1.5, 1.5) without CD by 69.3% and 76.5% when N is 10 and 40, respectively. This is because the collision detection capability can reduce the number of devices involved in the neighbor discovery procedure and the collision probability. That is, as more time slots are evaluated in PND with CD, less devices contend for the transmission of advertisement messages. In the same context, Figures 4 and 5 demonstrate that larger (or more aggressive) values of c_{coll} and c_{idle} exhibit

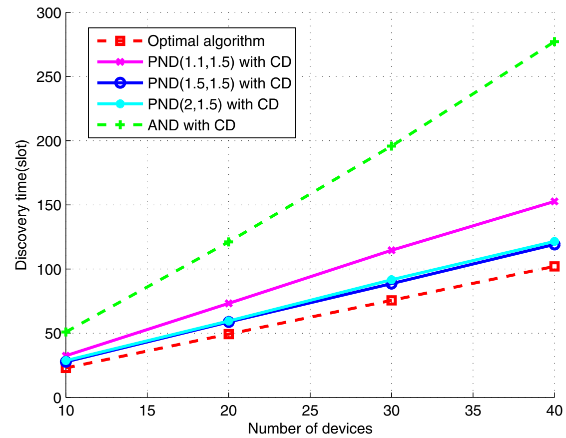


(a) Discovery time with varied c_{coll}.

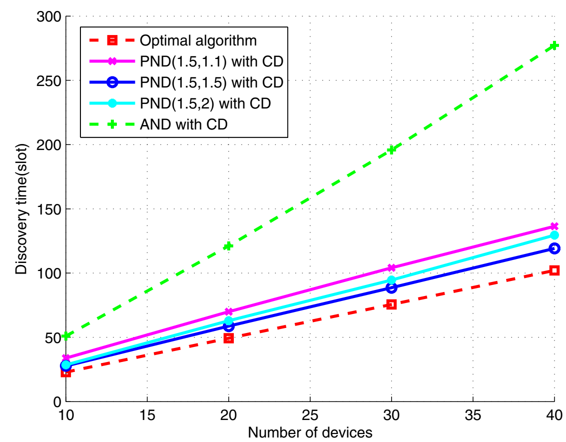


(b) Discovery time with varied c_{idle}.

Fig. 4. Neighbor discovery time of PND.



(a) Discovery time with varied c_{coll}.



(b) Discovery time with varied c_{idle}.

Fig. 5. Neighbor discovery time of PND with CD.

better neighbor discovery performance in PND with CD.

VI. Conclusion

In this paper, we have proposed a probabilistic neighbor discovery (PND) algorithm, which adjusts the transmission probability of advertisement messages in an adaptive manner. Simulation results reveal that PND with the MIMD policy can provide quick convergence on the optimal transmission probability and can reduce the neighbor discovery time compared to the ALOHA-like neighbor discovery algorithm. In addition, the collision detection capability can further improve the performance of PND significantly. In our future work, we will investigate how to extend PND in wireless networks supporting directional transmissions.

Acknowledgment

This research was supported in part by Business for Cooperative R&D between Industry, Academy, and Research Institute funded Korea Small and Medium Business Administration in 2012 (Grants No. C0002920) and in part by the MSIP, Korea, under the ITRC support program supervised by the NIPA (NIPA-2013-H0301-13-1002).

References

[1] S. Vasudevan, D. Towsley, D. Goeckel, and R. Khalili. "Neighbor Discovery in Wireless Networks and the Coupon Collector's Problem," *in Proc. Mobicom 2009.*

[2] X. An, R. V. Prasad, and I. Niemegeers, "Neighbor Discovery in 60 GHz Wireless Personal Area Networks," *in Proc. IEEE WoWMoM 2010.*

[3] L. You, Z. Yuan, P. Yang, and G. Chen, "ALOHA-like Neighbor Discovery for Low-Duty-Cycled Wireless Sensor Networks," *in IEEE WCNC 2011.*

[4] S. Vasudevan, M. Adler, D. Goeckel, and D. Towsley, "Efficient Algorithms for Neighbor Discovery in Wireless Networks," *IEEE/ACM Transactions on Networking,* vol. 21, no. 1, pp. 69-83, Feb. 2013.

[5] F. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part II–The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution," *IEEE Transactions on Communications,* vol. 23, no. 12, pp. 1417-1433, Dec. 1975.

[6] J. Peng, L. Cheng, and B. Sikdar, "A Wireless MAC Protocol with Collision Detection," *IEEE Transactions on Mobile Computing,* vol. 6, no. 12, pp. 1357-1369, Dec. 2007.

[7] S. Sen, R. Roy Choudhury, and S. Nelakuditi, "CSMA/CN: Carrier Sense Multiple Access with Collision Notification," *IEEE/ACM Transactions on Networking,* vol. 20, no. 2, pp. 544-556, Apr. 2012.