Between Neighbors: Neighbor Discovery Analysis in EH-IoTs

Shruti Devasenapathy*, Vijay S Rao*, R Venkatesha Prasad*, Ignas Niemegeers* and Abdur Rahim†

*Wireless and Mobile Communications,
Faculty of Electrical Engg., Mathematics and Computer Science,
Delft University of Technology,
Mekelweg 4, 2628CD Delft
The Netherlands
{S.Devasenapathy,V.Rao,R.R.VenkateshaPrasad,I.G.M.M.Niemegeers}@tudelft.nl
†CreateNet
abdur.rahim@create-net.org

Abstract—Devices in future Internet of Things (IoT) will be scavenging energy from the ambiance for all their operations. They face challenges in various aspects of network organization and operation due to the nature of ambient energy sources such as, solar insolation, vibration and motion. In this paper we analyze the classical two-way algorithm for neighbor discovery (ND) in an energy harvesting IoT. Through analysis, we outline the parameters that play an important role in ND performance such as node density, duty cycle, beamwidth and energy profile. We also provide simulation results to understand the impact of the energy storage element of energy harvesting devices in the ND process. We demonstrate that there exist trade-offs in choices for antenna beamwidth and node duty cycle, given node density and energy arrival rate. We show that the variations in energy availability impact ND performance. We also demonstrate that the right size of the storage buffer can smooth the effects of energy variability.

I. INTRODUCTION

In today's connected world, we have several means of communicating with others on the go. Not only this, we can also connect to various objects in our surroundings for various services. We are on the verge of a future where there will be thousands of inanimate objects to each human that will ceaselessly communicate with each other to support humans. In general this paradigm is termed as "Internet of Things" (IoT). The nodes or devices in IoT are predominantly sensors and actuators that will work towards better home and office automation, maintenance and control of operations within systems such as vehicles, process industries, stock management at stores and industries, and so on.

With the growth of number of these devices that would be networked to support various activities, it is impossible to power them continuously through grid or batteries. One way to power them continuously is through harvesting energy from the ambiance. In light of the number of IoT devices that are predicted to be employed (25 billion by 2015 [1]) and the nature of applications, it becomes important to study devices that employ energy harvesting technologies as we elaborate in this paper.

The importance of neighbor discovery in IoT devices is evident when considering the nature of these devices and networks that need perform self-management, self-healing and self-configuration. An IoT device needs to learn about its immediate environment to be capable of performing these tasks, thus justifying a dedicated study towards neighbor discovery protocols in this special class of networked devices.

Energy harvesting depends on the ambient source. It depends on the deployed location and on the type of the harvester as well. Energy harvesting at any node varies heavily with space and time across the deployed set of IoT devices, leading to the necessity of designing communication protocols that accommodates these variations. Specifically, in this paper we focus on the issue of neighbor discovery (ND) for energy harvesting IoT (EH-IoTs) devices. In traditional sensor networks, ND is performed implicitly. Given the variable instantaneous energies in EH-IoTs, however, the energy harvesting nodes can leave and re-enter the network. Thus, ND is no longer a trivial task in such networks and also it is not only performed at the deployment stage of the network but also at regular intervals. In EH-IoT networks, every node may see different energy availability e.g., a device with photovoltaic (PV) panel facing south and another facing north. Such heterogeneity implies that the burden of ND could be handed over to a node that sees more frequent or larger quantities of energy. If nodes are equipped with prior knowledge of energy availability through a reliable energy prediction algorithm, they could pro-actively support ND process.

It is interesting to investigate with both directional and omnidirectional antennas for the ND process in EH-IoTs. In the directional case, intuitively, the nodes' responses for discovery messages may have lesser collisions due to lesser node density, and hence may take lesser time for discovery of all the nodes. Additionally, this would result in energy savings, further contributing to lower discovery time.

In this paper we propose a general analytical model for ND in an EH-IoT setting. We make notes on the impact of important parameters - beamwidth, duty cycle, density – on performance, a detailed study of the effect of energy variability and its mitigation through the choice of energy storage capacity. We do this with the help of the analytical

model of a setup in which one EH node attempts ND to find its immediate neighbors (all EH-IoT devices) with an omnidirectional and directional antenna. Through numerical results from this model, we find the extent of impact of important parameters. These are supported with simulation results.

The organization of this paper is as follows. We introduce some pertinent related literature in Section II. We describe an ND algorithm that follows a simple three-way handshake for nodes to discover each other, as an analytical model in Section III. The parameters that influence ND performance are outlined with the help of numerical results in Section IV. The results of the simulation of this ND algorithm under a realistic energy regime are discussed in Section V. Numerical and simulation results are discussed and recommendations are provided in Section VI. Finally, Section VII concludes this paper with some recommendations for system and network choices.

II. RELATED WORK

ND in wireless sensor networks is not considered to be a problem by itself as it is traditionally performed by MAC protocols as an implicit operation. However, as Dutta and others point out in [2], ND is not a trivial problem in networks where it is not easy or practical to predict if and when a node will find a neighbor nearby. These networks include mobile networks in which energy is a constraint – e.g., battery operated ad hoc networks. With respect to low or optimal energy consumption, Madan and Lall present a minimum energy method for ND [3]. Their solution rests on the computation of a minimum energy graph at design time by solving a stochastic shortest path problem. Both Dutta and Madan consider energy conservation in constrained setups during ND. However, the problem of energy conservation is not primary in energy harvesting. Over a long duration of time, a node can receive sufficient energy to perform various operations, but instantaneous availability is limited. Thus, the major issue posed by harvesting is variations in energy availability and thus must be handled differently. Furthermore, storage of energy in devices such as supercapacitors introduces loss due to leakage, which implies it is not ideal to wait for energy accumulation in storage devices for use over a long period of time. Thus, the design of a network of EH-IoTs is non-trivial.

Iyer et al., define a protocol *NetDetect* where neighbor discovery is performed using periodic beacon transmissions [4]. Here, the rate of beaconing is based on the estimate of the number of nodes in the neighborhood. However in case of energy harvesting networks, a popular technique adopted for energy management is to adapt the duty cycle to the rate of energy harvesting [5], [6]. Such a rate adaptation causes additional complexity in ND process.

Various ND algorithms have been analyzed for wireless networks that use directional antennas. Vasudevan et al. [7] classify them into two major categories – direct and gossip

based. They present an analytical approach to comparing algorithms. The authors discuss antenna beamwidth selection based on the optimal transmission probability for best performance. Similarly, the effect of beamwidth and propagation models on the performance of ND protocols for 60 GHz networks is analyzed in detail by An et al. [8]. Analysis of ND in ad-hoc networks is discussed by An and Hekmat [9]. Several works deal with neighbor discovery in ad hoc networks [10], [3], [11]. Zhang and Li conduct a performance analysis of several random and scan-based algorithms for directional ND in ad hoc networks [12]. Their study concludes that an iterative scanning method performs better. We employ such an iterative scanning method in our study as well.

The impact of variations in energy availability on the ND process (whether omnidirectional or directional), as is observed in an energy harvesting system, has not been investigated to the best of our knowledge. In order to study this, it becomes important to understand the nature of energy harvesting sources. Energy arrival at a harvesting node in a natural environment is best modeled as a stochastic process due to the random nature of most natural sources such as sunlight and wind. Poggi and others demonstrate that the solar radiation recorded over a period of time can be mapped to a Markov process [13]. Similarly Ho et al. provide the methodology to model harvested energy as a non-stationary Markov process with added context - that is additional information about the environment in which the device is deployed[14]. Similarly, in our study, we model energy arrival as a stochastic process to emulate natural conditions. Thus, we shed some light on the impact of various important parameters and importantly varying energy availability on ND in an energy harvesting setup.

While there is a large body of work on the subject of neighbor discovery in ad-hoc networks and also in energy-constrained wireless networks, existing literatures do not sufficiently address ND specifically in energy harvesting networks. In this paper, we focus on the special circumstances of EH networks that warrant different solutions than those proposed before.

III. ANALYTICAL MODEL

In order to understand the factors that impact the ND process, we study the analytical model of the two-way ND process which a single node performs to discover all of its k neighbors. We assume that the number k is known a priori. Other assumptions are that each node can control the beamwidth of its antenna, all nodes operate at a duty cycle and each node is equipped with an energy harvester. Further, time is divided into equal slots each of which could refer to one millisecond (as we consider in our simulation study) for instance. The nodes are synchronized with respect to the slots i.e., two nodes waking up at a slot will wake up together. However, note that nodes choose their own wake-up and sleep times depending on their energy and duty cycle.

We consider a rectangular field in which nodes are placed at random. One of them is picked to be the "scanning node"
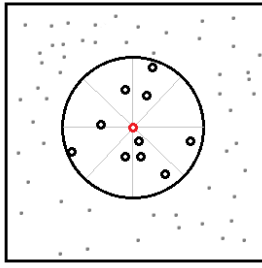
Fig. 1: Example Setting for ND in a set of EH-IoTs

A (marked in red in Fig 1) referred to as A. The scanning node is similar to a sink or a cluster head since it possesses higher processing capabilities. This scanning node attempts to discover all of its immediate neighbors $B_1, B_2, ..., B_k$ (marked as black circles) using the two-way ND process. We define immediate neighbors to be those nodes that fall into the radio range (given by the large circle) of the scanning node A. Further, the area that falls in the radio range of A is divided into sectors (as an example into 8 sectors marked with gray lines in Fig 1) that represent the area that A spans with its directional antenna.

Thus, we assume a hierarchical structure with a single node that acts pro-actively to initiate and perform a neighbor discovery process. This scenario can be expected, for example, in smart home settings where a single node behaves as the home controller or supernode. Also, even in a homogeneous setting, deployed nodes do not assume the role of a lead as soon as they come up. Instead, they look for a lead or cluster head and engage with it. Our assumption allows us to approach reality better than in a completely homogeneous model. Furthermore, this is an open problem for energy harvesting networks in general for the following reasons. Since adaptive duty cycling and varying energy conditions make it impossible for nodes to ensure the absence of other scanning nodes by simply listening long enough, nodes cannot arbitrarily choose to become scanning nodes themselves. An election process where nodes choose the node that becomes a cluster head is not possible before nodes become aware of their neighbors first, that is not before ND is performed.

The neighbor discovery process involves exchange of a set of handshake messages between the scanning node and its immediate neighbors. The scanning node initiates the process by sending out an ND packet. Any neighbor node that hears the ND packet responds to it with a response ND (RND) packet. If the scanning node receives the RND successfully, it sends an acknowledgment. If not, the neighbor node changes its next instant of wakeup and the process repeats. At the end of a single successful run of this process, the scanning node and a given neighbor have listed each other in their respective neighbor tables.

In this study, performance metrics considered are : ND time – the total time taken to discover all one-hop neighbor nodes and ND ratio – the ratio of number of found nodes to total

number of one-hop neighbor nodes. We focus on ND time which provides an understanding of the efficiency of the ND process.

A. Omnidirectional Neighbor Discovery

First, we understand the behavior of the omnidirectional transmitter. A must discover k nodes labeled B_1 to B_k (we refer to a single one of them simply as B). These are k nodes that happen to be within the radio link range of A (marked as black circles in Fig 1). In order to discover these nodes, A transmits with a probability P_{t_A} given as,

$$P_{t_A} = \frac{1}{N_{2way}} P_{eA} \qquad (1)$$

A attempts ND at regular intervals once every N_{2way} time slots. The parameter P_{eA} is the probability that A has the energy required to initiate and complete the ND process at that instant of time. This probability in a real system would be equal to the probability that the required amount of energy is available to node A. The parameter P_{t_A} would describe periodic discovery attempts if the device operated on a steady energy supply, e.g. mains supply. However, energy availability is random in an energy harvested device. Therefore, though the node is scheduled to perform discovery at regular intervals, the process can be best described as random due to the parameter P_{eA}.

Every node B listens for an ND message from A with a probability, P_{l_B} which is given as:

$$P_{l_B} = \frac{1}{T_B} P_{eB}, \qquad (2)$$

where T_B is the on duration of B_i (the node is ON for 1 time slot) and P_{eB} is the probability that B has the energy to respond to the ND message. Again, for a device running on a constant energy source, node B would listen for ND messages at fixed regular intervals. However, the variability in energy availability at given instances causes the listening interval to best described as random. It is important to note here that the instances at which A and B may perform their respective activities are fixed and regular, whether or not they do perform scheduled activities at a given instant is dictated by the availability of energy. Also, N_{2way} and T_B are chosen to be co-prime, in accordance with the Chinese remainder theorem [15], so that there is never a possibility that two nodes do not discover each other.

Thus, the probability that an ND packet transmitted by A reaches B successfully is given as:

$$P_{A \rightarrow B} = P_{t_A} P_{l_B} \qquad (3)$$

This also gives the probability P_{t_B} that node B that receives this ND packet responds to it by sending an RND. In order for the discovery process to be completed, B_k nodes must respond to A without their RNDs colliding with each other. The probability that of k nodes that have not been discovered by A of which only one responds is given as $(1 - P_{t_B})^{k-1}$. Thus

the probability that only a single node reaches the scanning node successfully (without collisions [1]) is given as:

$$P_{B \to A} = \binom{k}{1} P_{t_B} (1 - P_{t_B})^{k-1} \qquad (4)$$

From this expression it is possible to calculate the time required to find a given node B_i as,

$$NDTime(i) = \frac{1}{P_{B_i \to A}} \qquad (5)$$

The total time that is required to find all k nodes is given as,

$$NDTime = \sum_{i=1}^{k} \frac{1}{P_{B_i \to A}}, \qquad (6)$$

where i denotes the number of nodes out of k that have been found by A.

The conflict resolution mechanism assumed here can be described in a practical setup as a three-way handshake mechanism. The scanning node transmits an ND packet, waits for an response (RND) and retransmits the received RND. Thus both nodes are informed of the success or failure of this exchange if the ND and RND packets are received correctly at both ends. In case of a failure to receive a correct RND, the neighbor node shifts the instant of its next wakeup by a random number of time slots. This helps avoid the inadvertent synchronizing of two or more neighbor nodes. These assumptions are not factored into our analysis, since we focus here on describing the scanning node's performance and the conflict resolution mechanism is implemented only into neighbor nodes.

B. Directional Neighbor Discovery

Let us now consider a scanning node whose beamwidth is controlled such that it transmits only to a small sector of its radio link area. There are changes in the analysis that we address in this section. We label the directional scanning node A_d. As in the omnidirectional case, the probability of transmission at A_d is given as :

$$P_{t_{A_d}} = \frac{1}{N_{2way}} P_{eA_d}, \qquad (7)$$

and the probability that the neighbor node B is listening remains the same as before, given by Eq 2.

The probability that the node B is in the same sector as the scanning node is given as $\frac{\theta}{2\pi} = \frac{1}{N_s}$, where θ gives the beamwidth of the directional beam and N_s is the resultant number of sectors into which the circular field is divided. Thus the probability that node B responds to the ND packet from A_d is given as $P_{t_B}(1/N_s)$ where P_{t_B} is defined as before in the omnidirectional case. The probability that no other node responds to A_d depends on the number of nodes that fall within the beam of A_d. We define the probability that of k number of neighbor nodes there are j nodes in the same beam sector as our selected node B. In other words, the probability that the

[1] As we do not study the physical layer here, we assume that if an ND packet is transmitted without ND collisions, it can be received by devices in range with probability 1.

sector N_j containing node j is the same as sector N_B which contains node B is:

$$P_j = P[N_j = N_B] = \binom{N_s}{1} \binom{k-1}{j-1} \left(1 - \frac{1}{N_s}\right)^{k-j} \left(\frac{1}{N_s}\right)^j \qquad (8)$$

Finally, the probability that the node B is successfully discovered by node A_d is given as :

$$P_{B \to A_d} = \sum_{j=1}^{k} P_j \binom{j}{1} \frac{P_{t_B}}{N_s} \left(1 - \frac{P_{t_B}}{N_s}\right)^{j-1}, \qquad (9)$$

and this reduces to Eq 4 for $N_s = 1$. Again, the number of time slots required to discover a single node is given as $1/P_{B \to A_d}$ and the ND time for all k nodes is the summation for all nodes B_i :

$$NDTime = \sum_{i=1}^{k} \frac{1}{P_{B_i \to A_d}}, \qquad (10)$$

where $i = 1, 2, ...k$ denotes the number of nodes found by node A_d.

IV. NUMERICAL RESULTS

From the analysis above, we can list the parameters that define the performance of the ND process as below: (a) Energy availability (P_{eA}, P_{eB}), (b) Number of nodes or node density (k), (c) Node duty cycle (given by P_{t_A} and P_{t_B} (d) Beamwidth (which gives N_s). In order to understand the impact of each of these parameters on the performance of A and A_d we plotted numerical results.

A. Energy Availability

In Fig 2, we see numerical results from the analysis for the case that $k = 40$ under several energy availability probabilities $P_e = P_{eA} = P_{eB}$ for all nodes. In our analytical model, we have not considered the dynamics of an energy storage element. Hence, the numerical results indicate the performance of an ON-OFF system. By considering the energy source to be random, we allow the model to be applicable with to a variety of harvesting sources that may or may not be time-dependent in nature, e.g. vibration-based or wind energy based energy sources.

The numerical results from this analysis for the case of varying energy probabilities and a scanning node that has a beamwidth of $\theta = 45°$ is given in Fig 3. With lower energy probabilities, the performance of ND deteriorates.

B. Node Density

The ND time for various values of k or node density for both an omnidirectional and directional transmitter is observed in Fig 4. As can be seen, the trend seems to saturate at higher values of k. This behavior is due to the fact that once a node has been found, it does not respond to subsequent ND packets of the scanning node. This factor i that takes values 1 through k, (appearing in Eq 6 and Eq 10) represents the number of nodes found at a given instant of time during the ND process .
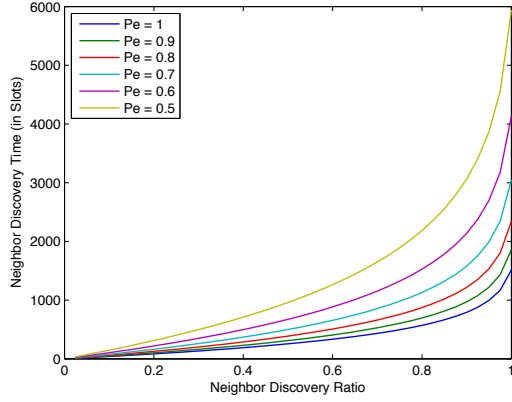
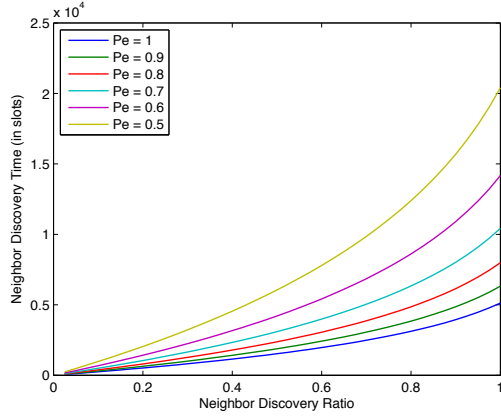Fig. 2: Omnidirectional Two-Way ND for Various Energy Probabilities

Fig. 3: Directional Two-Way ND for Various Energy Probabilities

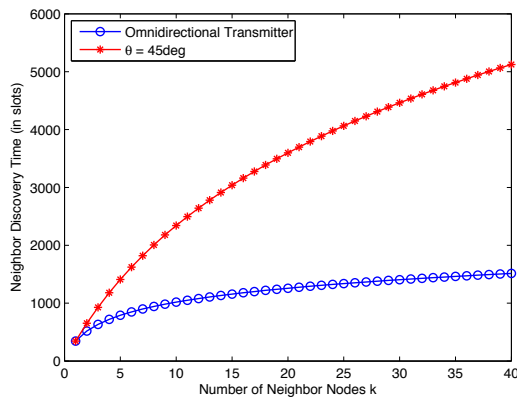Fig. 4: Performance of Two-Way ND for Various Node Densities

C. Node Duty Cycle

The duty cycle gives the probability that a responding node B is awake and hence hears the message to respond to the ND packet from the scanning node. Thus, the parameter of interest here is the probability that a neighbor node responds to the ND given by Eq 4 for the omnidirectional case and by Eq 9 for the directional case. Plotting the ND time against this parameter gives us insight into the advantage that directional transmission would provide to the ND process.
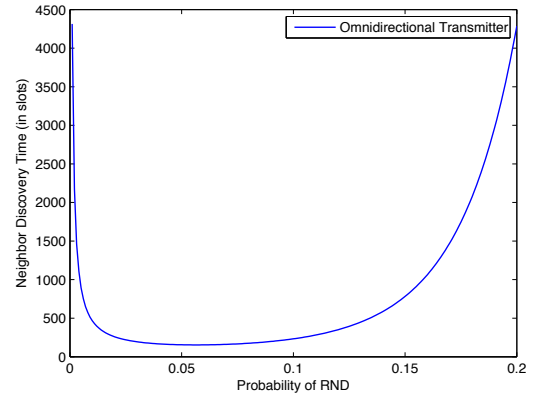
(a) Omnidirectional Case
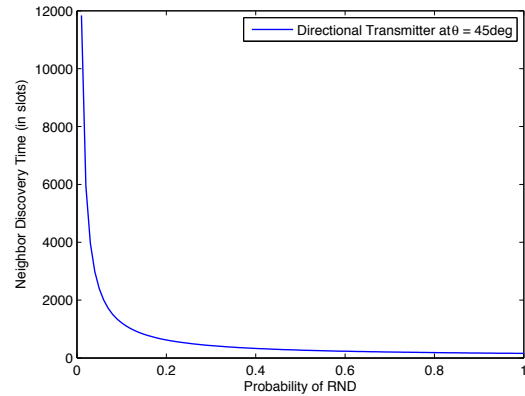
(b) Directional Case

Fig. 5: Effect of Response Probability on ND Time

On the one hand, we see in Fig 5(a) that the ND time increases dramatically, starting at the extremely low RND probability of 0.12. On the other hand, the directional transmitter benefits from the factor P_j as there is little impact of a high probability of response (in Fig 5(b)). In other words, since there is a low probability of several of the k nodes occupying the same sector, the ND time is relatively unaffected by the response probability.

D. Beamwidth

We can see in Fig 6 that the performance gets progressively worse with an increasing beamwidth. The major cause for this is the lower probability that at a given time node B is listening

in the same sector as the one in which A transmits. Another important factor is the variability of energy availability. We shall see the ameliorating effect of a storage buffer through simulation results.
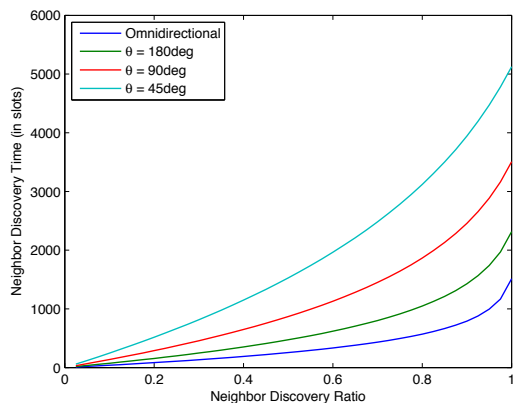

Fig. 6: Effect of Various Beamwidths on ND time

V. SIMULATION RESULTS

We simulated the setup for the two-way ND scheme for various parameters. Presented in this section are the results of the simulation averaged over 1000 runs for each case. We introduce an energy storage element here which is modeled on a supercapacitor with linear leakage. Energy arrives to the supercapacitor following a Poisson arrival process, where each arrival is a uniform random variable which denotes the amount of energy harvested. We denote the inter-arrival times of this process as IA. Every node has an energy storage element and will initiate or respond to ND process if it has energy greater than a threshold value. If energy is unavailable, ND is deferred till the next scheduled time slot. This energy model [2] differs from the ON-OFF energy model considered in Section III.

The energy model considered in the simulation setup is specific to an energy harvesting setup that consists of a harvesting sensor (e.g. solar panel or thermoelectric generator) with harvesting electronics used to step up and regulate harvested energy and an energy storage device that has very specific properties. However, our analytical energy model is a much simpler ON-OFF setup with no storage capacity factored in. This simple model can be applied with small modifications to describe any other harvesting setup. While our motive here is to make a case for the necessity of ND algorithms for energy harvesting systems, an analytical model of a global energy harvesting model remains an open problem to be explored further [17].

A. Effect of Energy Inter-arrival Times

We see the impact of varying IA values on the ND time in Fig 7. When $IA = 15$, energy arrival is infrequent and the system suffers from greater variation in energy availability.

[2]Further details on the simulation energy model and results can be found in the companion paper [16].
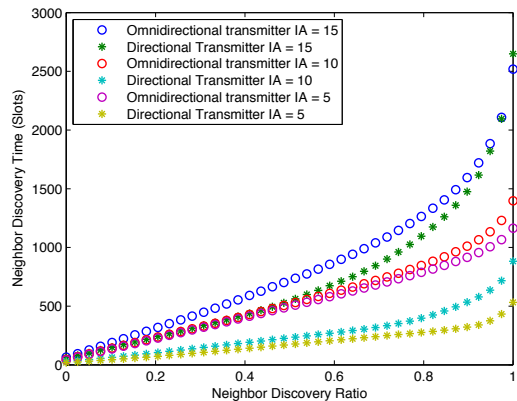

Fig. 7: Effect of Energy Interarrival Times for $k = 40$ on ND time

Under this condition, the omnidirectional scanning node outperforms the directional node. However, when energy availability improves, the directional node recovers substantially. We may attribute this behavior to three causes: (i) Lower energy availability impacts the directional node more than the omnidirectional node as we have observed from numerical results (ii) The directional node consumes more energy since it must transmit more ND packets. (iii) There is a smaller probability that neighbor nodes are listening in the same sector as the one in which the scanning node transmits – thus more energy is depleted from storage buffers and ND process gets deferred more often. However, it can be seen that the directional transmitter at $IA = 10$ performs even better than the omnidirectional transmitter that sees more frequent energy arrival at $IA = 5$. Thus we may conclude that the impact of energy variations on ND time is higher than that of beamwidth.

Though the energy model used to obtain numerical results in Section IV is different from the model in simulation, we see that the trends in Fig 7 match numerical results. This implies that our analytical model provides us with an upper bound for ND in energy harvesting systems, since they depict a scenario with no energy storage. We see that adding an energy storage buffer reduces the ND time considerably, which leads us to investigate the impact of size of storage element in the next subsection.

B. Effect of Energy Storage Capacity

In order to understand the impact of variations in energy availability during ND, we simulated the two-way process for different supercapacitor capacitance values 'C'. While the default value for C was $0.7F$ which corresponded to $3mJ$ of energy storage (for results seen in Fig 7), we see the ND time for various values of C in Fig 8. The study was conducted for the $IA = 15$ case to understand how the system behaves in the most adverse conditions.

As C increases, the ND time reduces. Since the storage buffer can store larger amounts of energy, the effects of constantly changing input energy conditions is reduced as the
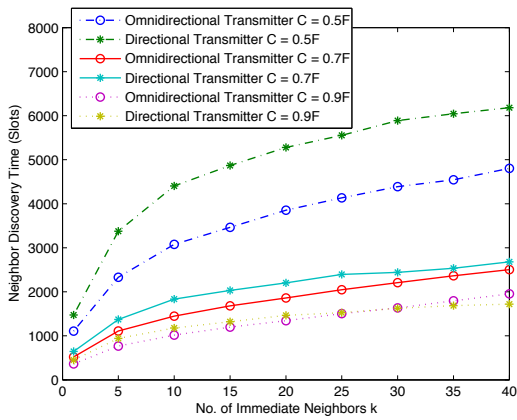
Fig. 8: Effect of Supercapacitor Capacity on ND time

supercapacitor now has a smoothing effect on these variations. Another interesting consequence of an increased C is that the difference in the ND time between the directional and omnidirectional scanning node reduces. For the case where C = $0.9F$, the directional scanning node matches the performance of the omnidirectional one for low values of k and even betters it for $k = 35$.
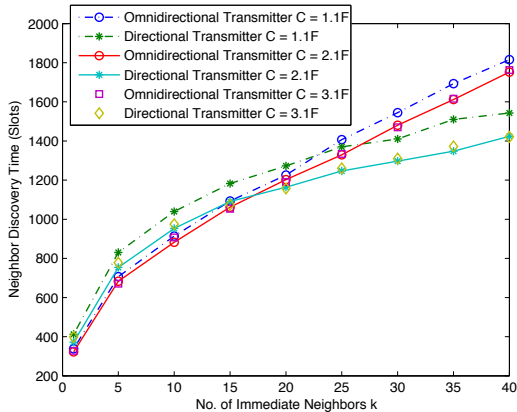

Fig. 9: ND Time does not improve after a threshold C

This improvement in performance is not seen beyond a threshold C. We see in Fig. 9 that there is no improvement in ND time from $2.1F$ to $3.1F$ and very little improvement from 1.1 to $2.1F$. It can be seen that the value of k at which the directional transmitter performs better than the omnidirectional one reduces from at $k = 35$ at C= $0.9F$, (seen in Fig. 8) to $k = 25$ at C = $1.1F$ and to $k = 20$ at C = $2.1F$. This allows us to conclude that energy variability does impact the directional transmitter more but these effects can be smoothed by using the right size of storage buffer.

VI. DISCUSSIONS

We have seen that the response probability of neighbor nodes has a great impact on the ND time. Response probability of B is in turn heavily impacted by energy availability in a storage buffer. If this energy is wasted, for example on collisions, the effect on performance is high. Collisions and the associated heavy losses occur more often in an omnidirectional case than in a directional case due to the factor P_j (Eq 8).

We have seen the large effect of node density and duty cycle on performance. The choice of these parameters must be taken into account during design and deployment in order to achieve best performance at least cost to the entire network – given network parameters such as connectivity and redundancy. Since there is an obvious trade-off between the node density and the duty cycle of neighbor nodes, it is important to choose one parameter given the other.

Next, importance must be given to the impact of beamwidth with respect to number of neighbors. For example, if the number of neighbors is low, it is advisable to use a larger beamwidth in interest of energy expenditure.

Finally, our numerical results suggest that though the directional transmitter sees lesser impact of response probability, it suffers heavily due to the decreased probability that nodes A and B are in the same sector at the same time. Variations in energy availability across the network also impact the directional antenna. Nevertheless, we have seen that by making right design choices for the energy storage buffer size, this impact can be handled well. So, an energy model for a given application setting must be first created in order to understand the frequency of arrival of energy that can be expected in that setting, to define the size of the storage buffer at design-time.

VII. CONCLUSION & FUTURE WORK

We described the analytical model for ND in a network of EH-IoT devices. With the help of this model, we outlined the impact of various important parameters – node density, node duty cycle, beamwidth and energy availability – on the ND process. Through numerical and simulation results, we described the extent of influence of these parameters on ND. We demonstrated the trade-offs that need to be resolved for good ND performance – tradeoffs between (i) node density and duty cycle, (ii) node density and antenna beamwidth, (iii) energy availability, energy storage and beamwidth. Finally, recommendations on how to make choices such that these tradeoffs were resolved were provided.

Future work must focus on studying ND algorithms for a more homogeneous setup. This remains a complex, open problem for EH networks. In a universally applicable energy harvesting model that remains an open issue, a non-linear leakage model for supercapacitors must be implemented.

VIII. ACKNOWLEDGMENT

REFERENCES

[1] *The state of Broadband 2012: Achieving digital inclusion for all.* Broadband Commission (ITU), Sep. 2012.

[2] P. Dutta and D. Culler, "Practical asynchronous neighbor discovery and rendezvous for mobile sensing applications," in *Proceedings of the 6th ACM conference on Embedded network sensor systems*, ser. SenSys '08. New York, NY, USA: ACM, 2008, pp. 71–84. [Online]. Available: http://doi.acm.org/10.1145/1460412.1460420

[3] R. Madan and S. Lall, "An energy-optimal algorithm for neighbor discovery in wireless sensor networks," *Mob. Netw. Appl.*, vol. 11, no. 3, pp. 317–326, Jun. 2006. [Online]. Available: http://dx.doi.org/10.1007/s11036-006-5185-x

[4] V. Iyer, A. Pruteanu, and S. Dulman, "Netdetect: Neighborhood discovery in wireless networks using adaptive beacons," in *Self-Adaptive and Self-Organizing Systems (SASO), 2011 Fifth IEEE International Conference on*, oct. 2011, pp. 31 –40.

[5] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Trans. Embed. Comput. Syst.*, vol. 6, no. 4, Sep. 2007. [Online]. Available: http://doi.acm.org/10.1145/1274858.1274870

[6] C. Moser, L. Thiele, D. Brunelli, and L. Benini, "Adaptive power management in energy harvesting systems," in *Design, Automation Test in Europe Conference Exhibition, 2007. DATE '07*, april 2007, pp. 1 –6.

[7] S. Vasudevan, J. Kurose, and D. Towsley, "On neighbor discovery in wireless networks with directional antennas," in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, vol. 4, march 2005, pp. 2502 – 2512 vol. 4.

[8] X. An, R. Prasad, and I. Niemegeers, "Impact of antenna pattern and link model on directional neighbor discovery in 60 ghz networks," *Wireless Communications, IEEE Transactions on*, vol. 10, no. 5, pp. 1435 –1447, may 2011.

[9] X. An and R. Hekmat, "Self-adaptive neighbor discovery in ad hoc networks with directional antennas," in *Mobile and Wireless Communications Summit, 2007. 16th IST*, july 2007, pp. 1 –5.

[10] R. Murawski, E. Felemban, E. Ekici, S. Park, S. Yoo, K. Lee, J. Park, and Z. H. Mir, "Neighbor discovery in wireless networks with sectored antennas," *Ad Hoc Networks*, vol. 10, no. 1, pp. 1 – 18, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870511000771

[11] G. Jakllari, W. Luo, and S. Krishnamurthy, "An integrated neighbor discovery and mac protocol for ad hoc networks using directional antennas," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 3, pp. 1114 –1024, march 2007.

[12] Z. Zhang and B. Li, "Neighbor discovery in mobile ad hoc self-configuring networks with directional antennas: algorithms and comparisons," *Trans. Wireless. Comm.*, vol. 7, no. 5, pp. 1540–1549, May 2008. [Online]. Available: http://dx.doi.org/10.1109/TWC.2008.05908

[13] P. Poggi, G. Notton, M. Muselli, and A. Louche, "Stochastic study of hourly total solar radiation in corsica using a markov model," *International Journal of Climatology*, vol. 20, no. 14, pp. 1843–1860, 2000. [Online]. Available: http://dx.doi.org/10.1002/1097-0088(20001130)20:14¡1843::AID-JOC561¿3.0.CO;2-O

[14] C. K. Ho, P. D. Khoa, and P. C. Ming, "Markovian models for harvested energy in wireless communications," in *Communication Systems (ICCS), 2010 IEEE International Conference on*, Nov. 2010, pp. 311 –315.

[15] M. H. Niven I, Zuckerman H.S, *An Introduction to the Theory of Numbers*. John Wiley & Sons, 1991.

[16] S. Devasenapathy, R. V. Prasad, V. S. Rao, and I. Niemegeers, "Impact of antenna directionality and energy harvesting rate on neighbor discovery in eh-iots," in *Proceedings of the 10th Annual IEEE-CCNC Smart Spaces and Sensor Networks*, Las Vegas, NV, USA, 2013.

[17] R. V. Prasad, S. Devasenapathy, V. S. Rao, and J. Vazifehdan, "Reincarnation over the air: Energy harvesting devices and networks," *IEEE Communications Surveys and Tutorials*, 2013.