

Impact of antenna directionality and energy harvesting rate on Neighbor Discovery in EH-IoTs

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Abstract—Homes, offices and vehicles are getting networked. This will enable context aware, autonomous operation of many support systems that could be controlled remotely. To achieve this there would be a large number of tiny devices – sensors and actuators – which are networked and they are termed generally as Internet of Things (IoT) devices. In future, they will be powered through harvested energy from the ambience to enable perennial lifetime and minimal manual maintenance. Some examples of energy sources are photovoltaic panels and piezoelectric crystals. Several challenges arise due to the nature of sources of energy. One of these challenges is that the devices (nodes) leave and re-enter networks due to fluctuating availability of harvested energy. As a result, the neighbor table maintained at each node changes quite often leading to complications in forming and maintaining routes. In fact initial neighbor discovery (ND) itself is a difficult task. Further, usage of directional antennas would increase the time taken to complete ND. We study such a network through exhaustive simulation study considering various parameters. We demonstrate the benefits and challenges of using directional antennas for ND. We present a scheme that nodes could use to discover their neighbor during initial deployment and another scheme that could be used for subsequent discovery on re-entry into the network. We show that a dedicated ND protocol is necessary for energy harvesting networks and that directional ND is beneficial in these networks under some circumstances.

I. INTRODUCTION & MOTIVATION

Miniaturization of sensors and actuators including the communication module has triggered an enormous growth of wireless sensor and actuators network (WSAN). These devices¹ are networked and could be accessed anytime and from anywhere. This class of networked WSANs systems are identified as Internet of Things (IoT). Future IoT devices are required to be powered by harvesting energy from the ambience. IoT devices are typically of low computation capacity, low radio range, little or no non-volatile memory storage. These Energy Harvesting Internet of Things (EH-IoT) devices have the additional challenge of functioning with sporadic energy availability.

In this paper we focus our attention on the problem of neighbor discovery (ND) in a network consisting of these EH-IoT nodes. ND is performed implicitly in traditional sensor networks. Further, a popular energy management technique in energy harvesting networks is duty cycle adaptation to the rate of energy harvested. Moreover, though energy availability in theory is perennial, power availability is not guaranteed at

every instant. Thus, 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. One of the peculiarities of EH-IoT networks is that every node may see different energy availability e.g., a device with photovoltaic (PV) panel facing south and 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 or powered by grid. If nodes are equipped with prior knowledge of energy availability through a reliable energy prediction algorithm, they could pro-actively support ND process.

In such a scenario we require a distributed or cooperative ND protocol, which is dealt with in this article. The contributions of this article are manifold. We first provide a scenario where ND process is studied in an EH-IoT network i.e., energy harvesting network. Further, we propose to use directional antennas for ND, since nodes can transmit at lower transmit powers, reducing their instantaneous power requirement. We shall see a major improvement over omnidirectional transmission by also reducing interference. We also study and propose protocols for re-entering nodes' discovery in an already deployed energy harvested network.

The rest of the paper is organized as follows: Section II summarizes related literature. Section III describes the ND scenarios we consider, the assumptions that we make and the details of the simulation setup. Then, we describe the effects of various parameters on the performance metrics, discuss the effects and consequences of these effects in Section IV. Finally, we present some suggestions for future work and conclude in Section V.

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 [1], 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 [1].

Similarly Iyer et al., suggest that beaconing rate must be based on the estimate of the neighborhood size [2]. Such an

¹We use the terms device and node interchangeably.

estimate of neighborhood size is calculated using the *NetDetect* algorithm that uses a maximum likelihood estimator which is fed with the number of errors occurring on the wireless channel. 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 [3]. Such a rate adaptation causes additional complexity in ND process.

Cohen and Kapchits describe a cooperative scheme for continuous ND which is performed by nodes in collaboration with known neighbors to find a node that may have recently entered the network [4]. Such a discovery process is different from the initial discovery process when no node is aware of the other. Again, the application of this scheme to energy harvesting networks is not straight forward as the nodes that have already been discovered by their neighbors would attempt to perform initial ND again. Thus, there would be a heavy overhead caused by nodes trying to discover neighbors who are already aware of them. A node that suffers heavy fluctuation between on and off state due to very low energy availability could potentially cause congestions by re-initiating the ND process in its vicinity repeatedly.

Discovery in wireless networks using directional antennas has been studied by Vasudevan and others [5] where the authors describe direct and gossip based algorithms. ND protocols in ad hoc wireless networks using directional antennas have been described by An and Hekmat [6]. They describe a hand shake based directional ND scheme and study its performance. An and others describe the various protocols that can be used for ND and the impact of beamwidth and link models on these protocols [7]. Each of these studies, describe the benefits of directional antennas in discovery and provide an analytical model for the same. However, they do not expand on a network in which nodes duty cycle due to non-availability of continuous source of power.

Thus we study the effects of infrequent energy arrival and variable beamwidth on the neighbor discovery process in EH-IoT nodes. In the next section we describe our simulation setup and our model.

III. SYSTEM MODEL & SIMULATION SETUP

We consider a network of EH-IoT devices. We assume that each node is equipped with an antenna whose beamwidth can be electronically switched similar to SPIDA as described by Nilsson [8]. We assume that it is possible to choose the beamwidth at which the transmitter may transmit ranging from 45° to 360° at which the transmitter becomes an ideal omnidirectional transmitter. We assume that there are ideal transmission conditions and link variations are not considered in this study. Further, we assume that time is divided into slots. In this study we take one time slot to be equal to one millisecond. We focus our attention on the network that has just been deployed. Every node in the network is powered by an energy harvester such as a photovoltaic panel, thermoelectric generator or vibration harvester. We assume that all nodes may or may not be powered by the same type of harvester. Thus the energy opportunities of each node in

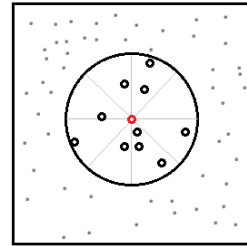


Fig. 1: Node Placement in System Setup

the network could be different from the other. In an indoor or home setting we can visualize this heterogeneity, since energy harvested depends on where the nodes are placed and the type of harvesting. For example, if a node is placed near windows they could use solar harvesting and if placed near the walls could use thermoelectric generation to bank on the difference in temperature in the insulation. In our study, we initially consider the ND process occurring in a single node that we label as “scanning node” or **A**. The assumption is that this node has been marked to perform this process before deployment and no other node attempts discovery. In an actual setting this assumption may not be unrealistic since, in a home setting this node could be a “super node” that acts as the home controller which is powered by a large harvester or the grid even. We assume that the node performing discovery is aware of the exact number of its neighbors ‘ k ’. However, a more homogeneous network must be modeled and studied for a truly ad hoc network. Now, we address different types of ND processes in the sequel.

A. Two-Way ND

1) *Omnidirectional Two-Way ND*: First, we consider an omnidirectional scanning node at the center of a circular field whose radius represents the radio link range of the node (See Fig 1). This scanning node attempts to find its immediate (single hop) neighbors which lie in random locations within the circular field. We assume that every node has a truly omnidirectional antenna and is on the same horizontal plane as every other node. We assume that there is no synchronization between nodes but all nodes follow time-slotted operation. All nodes other than the scanning node sleep for T_{off} ms and are awake for T_{on} ms. The algorithm for this method is shown in Alg. 1.

2) *Directional Two-Way ND*: We then consider the case where the scanning node has a directional antenna with a beamwidth θ and thus the circular field is divided into $\frac{2\pi}{\theta}$ sectors. The scanning node transmits DND packets in a fashion similar to the wheeled-iteration method [6], i.e., the scanning node transmits a DND packet and awaits an RND in each of the sectors 1 through $\frac{2\pi}{\theta}$ sequentially. Thus the total transmission time for the scanning node is $2\tau \cdot \frac{2\pi}{\theta}$. The assumptions about the neighboring nodes remain the same as before. The algorithm is described in Alg. 2.

Algorithm 1 Omnidirectional Two-Way ND algorithm.

At the scanning node **A** when having sufficient energy:
while all k neighbors are not found **do**
 Advertise a neighbor discovery (OND) packet using omnidirectional antenna
 Wait for Reply ND (RND) packet in the next τ ms
if RND for a neighbor x is successfully received **then**
 Mark x as found
 Send a broadcast packet saying x has been found
end if
 Sleep for $(N_{2way} - 2\tau)$ ms
end while

At a neighbor node y with sufficient energy:
if OND packet is received successfully **then**
 Send a Reply ND (RND) packet
 Wait for **A** to check if y is found
if y is not found by **A** **then**
 Randomize the next wake-up time
end if
end if

Algorithm 2 Directional Two-Way ND algorithm.

At the scanning node **A** when having sufficient energy:
while all k neighbors are not found **do**
for all s where s is a sector from sector 1 through sector $\frac{2\pi}{\theta}$ **do**
 Advertise a neighbor discovery (DND) packet using an directional antenna with beamwidth θ
 Wait for Reply ND (RND) packet in the next τ ms
if RND for a neighbor x is successfully received **then**
 Mark x as found
 Send a broadcast packet saying x has been found
end if
end for
 Sleep for $(N_{2way} - 2\tau \cdot \frac{2\pi}{\theta})$ ms
end while

At a neighbor node y with sufficient energy:
if DND packet is received successfully **then**
 Send a Reply ND (RND) packet
 Wait for **A** to check if y is found
if y is not found by **A** **then**
 Randomize the next wake-up time
end if
end if

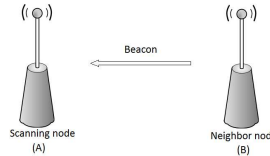


Fig. 2: One Way Neighbor Discovery

B. One-Way ND

Let us consider a connected energy harvesting network, where nodes have discovered their neighbors and are now performing network operations such as sensing and data transmission. However, with energy harvesting nodes in the network, when nodes constantly leave and re-enter the network, storing a neighbor table in non-volatile flash memory is often too expensive for nodes to perform especially if node density is high and also from the point of view of available energy. In such a case, it is more economical for a node to attempt to rediscover its neighboring nodes every time it re-enters the network. However, a two-way ND process could be avoided in this case as most nodes are already aware of all their neighboring nodes. We propose that all nodes in a connected network send out beacons. These beacons can then be heard by the newly “reborn” sensor nodes and it is used to discover their neighbors. Such a beaconing could be useful not just for ND but also to convey important information such as synchronization as in S-MAC [9] and/or as a signal that a node is still or active in the network.

C. Energy Model

In this subsection we describe the modeling of the energy arrival process, the energy consumed by the nodes and the behavior of the energy storage elements.

1) *Energy Harvesting (Arrival) Process*: Though the energy harvesting is a continuous process, the nodes would not be able to use the tiny amount of harvested energy as and when it is harvested. This is due to the limitation of the hardware. The nodes start working only when there is enough energy in their supercapacitors or batteries. To substantiate this claim let us take a look at harvesting electronics. They make use of DC-DC converters which require a minimum power level to start operating. Thus there exists a threshold above which the energy needs to be harvested. Thus, during a long absence of harvesting opportunity or if the amount of energy harvested is less, the nodes would be off. The quantity of arrival is randomized to emulate a varying energy availability level similar to the varying power at the harvesting sources, e.g., a solar panel at noon versus at sunset.

We call this as an energy arrival model at the harvesting node and we assume it to follow a Poisson arrival process. That is, the time between the arrivals of two discrete bursts/packets of energy is exponentially distributed. We use the term energy inter-arrival (or IA) time to indicate that the time between two consecutive arrivals of energy. Thus an energy regime that sees an IA time of 15 time slots is injected with a random quantity

of energy every 15 time slots on an average. While it is difficult to visualize the arrival of energy in this manner from a solar panel, it is natural to observe this from a piezoelectric crystal harvesting energy from structural vibrations.

Harvested energy is accumulated in an energy storage element modeled as a supercapacitor. We account for the loss due to leakage current.

2) *Energy Consumption at Nodes*: Each node is assumed to be aware of its energy availability in the storage buffer. A node initiates or responds to an ND process only if it has energy required for the entire process. For example, scanning node with directional capability in the two-way discovery process would start transmission in Sector 1 only if it has energy to transmit to and receive from all sectors.

D. Conflict Resolution

Collisions occurring at the scanning node due to multiple nodes transmitting at the same time have to be dealt with effectively for successful discovery². In the two-way discovery method discussed above, every RND received by the scanning node is retransmitted to the neighbor nodes. Thus, if the neighbor nodes receive a packet that does not match the packet that it has just sent, it can detect that a collision has occurred. When such a collision is detected, the node randomly reschedules the instant at which it wakes up next. Since each node that detects this collision reschedules its timers, the probability of a collision during the next ND period is reduced. If the received and transmitted packets match, the node that transmitted the ND packet does not respond to any subsequent ND packets, thus as nodes are found, the rate at which collisions are experienced must reduce. In the one-way discovery process, as there is no feedback from the passive scanning node, each neighbor node simply randomizes the time slot at which it transmits the next ND packet. To compare different categories of ND and also to study the effect of various parameters we use the following metrics (similar to [7]): (a) ND ratio is the ratio of found nodes to total number of neighbor nodes. (b) ND time is the time taken to find all k neighboring nodes. (c) ND energy is the energy required at the scanning node to discover k number of neighbors. It includes the energy required for the DND or OND packet, for reception and the energy cost for acknowledgments.

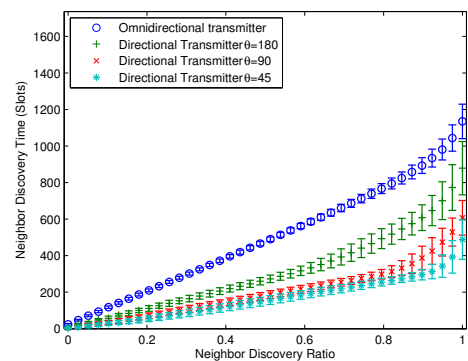
IV. RESULTS & DISCUSSIONS

In this section, we address the effects of different beamwidths and energy inter-arrival times on the two-way omnidirectional and directional cases. Following this, we study the performance of the one-way ND case at various energy regimes and discuss how it compares with two-way discovery.

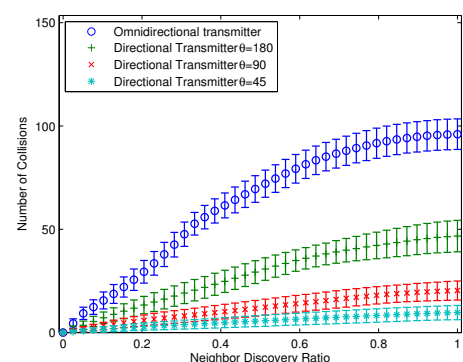
A. Two-Way ND

1) *Effect of Beamwidth*: The study of the effect of beamwidth was conducted in the case that $k = 40$ nodes and

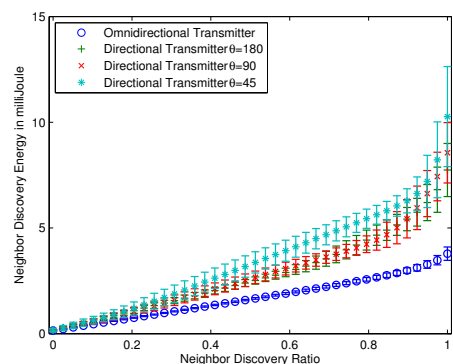
²As we do not perform physical layer simulation, we assume that if an ND packet is transmitted without ND collisions it can be received by devices in range with probability 1.



(a) Required Number of Time Slots for Discovery



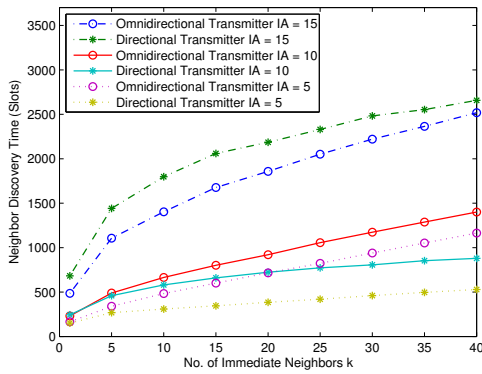
(b) Number of Response Collisions



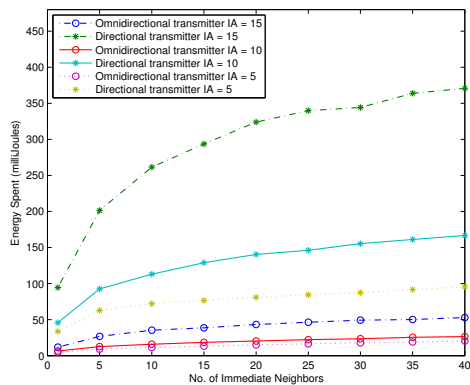
(c) Energy Spent

Fig. 3: Effect of Beamwidth

that all nodes, including the scanning node, have excess energy availability i.e., energy inter-arrival time is 0. Neighboring nodes operate at 20% duty cycle. The advantage of using a directional scanning node is evident from Fig. 3 which shows the ND time required to find each neighbor node and shows the mean and standard deviation of samples taken over 1000 iterations of the procedure. As the beamwidth of the scanning node decreases collisions that occur among responding nodes go down. Thus the required ND time reduces. As the percentage of nodes discovered increases, we can observe that the deviation from the mean increases. Such an



(a) Required Number of Time Slots for Discovery



(b) Required Energy for Discovery

Fig. 4: Effect of Energy Inter-arrival Times

increase is the result of the randomization of the back-off time that is performed for the purpose of conflict resolution. In Fig. 3(b) we see the cumulative number of collisions that occurred before discovering each of the 40 nodes. In case of omnidirectional scanning node, a sharp rise can be seen in the number of collisions till about 40% of the nodes are found. Beyond this point, the number of collisions saturates visibly. The reason for this is that as each node is found, the probability of a collision kept reducing as the nodes that are already found in the previous slots no longer respond to the subsequent ND packets.

The energy required for finding all 40 nodes can be seen in Fig.3(c). We assume that the scanning node can transmit to the same link range for a smaller transmit power. Yet, the advantage that the scanning node has in lower ND time for low beamwidth is offset by the higher energy consumption due to increased number of transmissions. Thus, at $\theta = 45^\circ$ the quantity of energy spent by the scanning node is highest and reduces with higher beamwidth.

2) *Effect of Inter-arrival Times of Energy* : The effect of inter-arrival times on the ND can be seen in Fig. 4. As we described previously, energy arrives at each of the nodes including the scanning node as a Poisson arrival process with

an inter-arrival time of 15, 10 and 5 time slots.

The time or number of slots required in each case to find neighbor nodes is recorded for both an omnidirectional and a directional scanning node ($\theta = 45^\circ$) in Fig. 4(a). As intuition suggests, the performance of the scanning node in terms of ND times is worse at low energy arrival rates. However it is interesting to see the behavior of the directional node versus the omnidirectional one. When the inter-arrival time is 15 time slots, the omnidirectional scanning node outperforms the directional node. This is caused by the excess energy that the directional node must spend in comparison with the omnidirectional node as seen in Fig 4(b). Since the nodes in the vicinity of the scanning node in the IA = 15 case suffer from lack of energy, they respond less frequently to the ND packets of the scanning node. As a result, the scanning node bears the brunt and has to spend a longer time and energy attempting discovery. Furthermore, as the directional node defers the ND process to a time when it has sufficient energy to carry out discovery in all sectors, there is a further increase in its ND time.

Implications: We now discuss some implications of the effect of beamwidth and rate of energy arrival on ND. While a directional scanning node is capable of better performance due to lesser interference, at very low energy availability, the directional antenna loses its advantage due to the larger number of ND packets and hence higher energy consumption. We initially assumed that the scanning node was in some way more endowed than its neighbor nodes which is why it pro-actively took on the role of finding its neighbors. In the directional discovery case, the onus of the excess energy consumption is only on the scanning node. Obviously, neighbor nodes waste lesser energy on collisions in this case. Thus the energy spent across the network is reduced and this makes such an option more profitable to a network deployed in a setting where energy availability is a major concern. Though this is at the cost of lower performance, over a long run, it can be argued that this network will be able to maintain connectivity for a longer duration due to fewer numbers of nodes dying out due to high energy consumption in the ND process itself. In order to increase the advantages of the directional scanning node, a better scheme could be devised by choosing a wider θ such that the benefits of both lesser interference and lower number of DND packets can be enjoyed.

In adverse conditions, if even the supposedly well-endowed scanning node has very low energy availability, we must distribute the burden among the other nodes. From the results we can understand that there is a threshold on inter-arrival time of energy below which it is advisable to perform directional ND. Here our results indicate that this inter-arrival time is 10 time slots. Nevertheless, this threshold is dependent on the transceiver chip used as the difference between energy consumed for different transmit powers varies widely among the various commercial offerings today. If there is a chip that provides lower energy requirement (than we consider here) for its lowest transmit power option, this threshold would not

apply and probably would not be required any more.

B. One-way ND

The scanning node behaves like a simple receiver in this study. Since we propose that this scheme be used for continuous ND, we must ensure that this method has the least possible overhead. However, as mentioned earlier the beaconing that we expect neighbor nodes to perform is multi-purpose and the overhead is not strictly for the ND process alone. Hence we focus only on the energy spent at the scanning node.

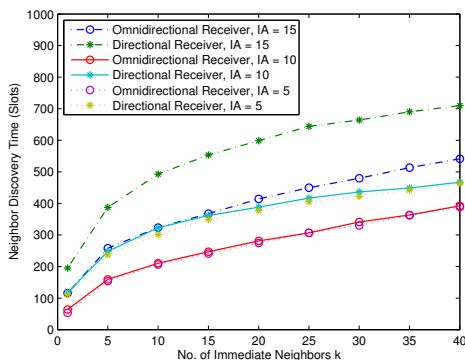


Fig. 5: Performance of One-Way ND Betters Two-Way at Various IA

As can be seen from the Fig. 5 the directional scanning node ($\theta=45^\circ$) takes a longer time to discover all of its neighbors than the omnidirectional node. At longer energy inter-arrival times, the directional scanning node performs worse as all nodes defer listening for an ND packet to a time when energy is available.

In conclusion, the one-way ND scheme can be implemented for ND with the scanning node acting as an omnidirectional receiver. The advantage of this method is that the node attempting to discover its neighbors has a low energy overhead and requires lesser ND time than the two-way scheme. However, the scheme is not ideal for initial discovery as bi-directional discovery does not occur here. It can be used for continuous ND such that the energy overhead across the network is minimized.

V. CONCLUSION & FUTURE WORK

Due to the fluctuation of instantaneous energy availability in EH-IoT devices, networks suffer from a lack of synchronism and periodicity in node sleep and wake up times. We demonstrated that these conditions have an impact on the ND process. We presented results of a simulation study that indicate the advantages of using a directional ND scheme for the two-way discovery scheme under certain energy regimes. We also studied the impact of the beamwidth of the directional scanning node. We discussed the importance of continuous ND and the overhead of a one-way discovery scheme for this process.

We considered a linear relationship between leakage current in the storage element with the stored energy. However, studies

suggest that this relationship is more complicated. In future studies, accurate modeling of the energy storage element must be included. Furthermore, we do not study the effects of the size of the storage element here. If we consider a larger supercapacitor, the effect of a heavily varying energy availability may be smoothed.

We consider nodes to form clusters that have a specially endowed super node that performs initial ND. In order to present a generalized solution, a model in which every node initiates ND processes of its own must be studied and understood. This homogeneous network would be an extension of the model we have studied here.

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