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Energy-aware Randomized Neighbor Discovery Protocol based on Collision Detection in Wireless Ad Hoc Networks

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Abstract In wireless ad hoc networks, neighbor discovery is necessary as an initial step. In this work we present LECDH (Low Energy Collision Detection Hello), an energy-aware randomized handshake-based neighbor discovery protocol for static environments. We carried out simulations through Castalia 3.2 simulator and compared LECDH with an existing protocol EAH (Energy Aware Hello) used as reference. We conclude that the proposal outperforms the reference protocol both in one-hop and multi-hop environments in terms of Energy consumption, Discovery time, Number of discovered neighbors, Throughput, and Discoveries per packet sent, for high duty cycles. Moreover, for low number of nodes in LECDH, as the duty cycle is reduced the performance is better according to all 5 metrics in both environments. Overall, we found that our proposal follows more realistic assumptions and still allows nodes to succeed at discovering all their neighbors almost with probability 1. Moreover, a qualitative comparison of the reference solution and our proposal is included in this paper.

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1 Introduction

Wireless ad hoc networks do not rely on an infrastructure after they have been deployed, and the devices include transceivers that provide a very limited transmission range (typically below 500 meters) [1,2]. In this type of networks, some nodes can send messages directly to their one-hop neighbors, whereas others need to forward information not intended to its own use in a multi-hop way, thus every node must have routing capabilities. [3,4].

In this type of networks, the nodes must be capable of self-configuring. Since the number of neighbors is unknown, neighbor discovery techniques are necessary as a main step after the deployment [5,6].

Basically, this type of networks can be classified as: (1) static (e.g., sensor networks, being the nodes placed in a field [7] in order to detect humidity) or (2) mobile (e.g., vehicles that have appropriate transceivers [8]).

Neighbor Discovery protocols can be (1) randomized, each node beginning to transmit in a randomly time or transmission probability, and achieve to discover all the neighbors in an amount of time with high probability different from 1, or (2) deterministic, each node transmitting following a schedule and achieves a discovery probability 1.

Energy efficiency is also an important point to take into account, since the devices are powered by batteries that last an amount of time. For this reason, the protocol presented in this paper mainly aims at reducing energy consumption.

Wireless ad hoc networks have many application areas [9], such as industrial, (e.g., mesh networks), medical (e.g., patient monitoring), and agriculture.

In this work we focus on the neighbor discovery in the context of static one-hop and multi-hop environments by presenting an energy-aware proposal LECDH (Low Energy Collision Detection Hello) in the presence of channel collisions.

Our proposal is compared against an existing protocol: the EAH (Energy Aware Hello) [3]. The main problem of EAH is that it does not achieve a discovery probability 1, and the nodes ignore the termination condition, i.e., they finish after a finite number of rounds. For comparison purposes, our proposal and EAH have been simulated through Castalia 3.2 [10].

As novelty, our proposal faces the current challenges introduced by prior works and introduces an energy-efficient randomized two-way handshake protocol. In this protocol no schedule is used, it deals with collisions, operates under more realistic assumptions, and ignores some network parameters, and the protocol is tailored for static environments.

The main contributions of this work are: (i) proposal LECDH, an energy-aware randomized collision detection based protocol that extends Hello protocol, with fixed slot width, discovers all the neighbors almost with probability 1, knows the termination condition, does not follow a transmission schedule, ignore the number of nodes, and it is appropriate for one-hop and multi-hop environments, (ii) a qualitative comparison of the EAH protocol and our proposal, (iii) an implementation in Castalia 3.2 and performance comparison of our proposal against the EAH protocol, for different duty cycles.

The rest of the paper is organized as follows: A description of related work can be found in section 2, our proposal, assumptions and model are included in section 3, a qualitative comparison of our proposal against the reference protocol, simulation scenario, and simulation results are addressed in section 4; in section 5 some conclusions are made.

2 Related Work

This section presents some protocols related to our work.

Next, some randomized neighbor discovery protocols from the literature are discussed. The family of Birthday protocols [7] succeed at maximizing the neighbor discovery probability, [3] focuses on the effects of collisions and presents two similar protocols, i.e., Hello protocol and the Energy Aware Hello protocol which is used as reference for our work. PSBA [11] is an energy efficient randomized proposal tailored for low duty cycle mobile WSN, Panda [12] is a highly practical generalized randomized proposal that has a real-world implementation in a EH ultra-low-power node. Nihao [13] is an asynchronous protocol which aims at reducing energy consumption at low duty cycles and has an available implementation on TinyOS 2.1.2.

Several energy-aware deterministic neighbor discovery protocols can be found in the literature, i.e., [14], [15], [16], [17], [18], [19].

All the proposals presented so far are asynchronous, they operate at low duty cycles, they are all suitable for its usage in symmetric and asymmetric environments except [15], all the deterministic protocols and PSBA [11] can be used in MANETs, while [12], [13], [14], [16], [17] and [19] provide a real-world implementation.

Among more recent works, KPND [20] is based on a mobility prediction model using both Kalman filter theory and hello messaging, [21] uses mobility prediction to achieve the discovery, [22] is a routing protocol for VANETs. [23] takes the advantages of radar in MTC (Machine-type communication), CRA [24] integrates radar and communication, [25] is used in highly dynamic resource constrained MANETs. [26] is a cross-layer neighbor discovery protocol for large-scale networks that combines TDMA, network clustering and GPS to find the neighbors, in [27] the discovery is modeled as a learning automaton to be used in dense networks. [28] proposes a 2-way random handshaking protocol, and a scan based protocol is presented in [29], RCI-SBA [30] uses radar and directional antennas, [2] uses social information recognition and a wake-up radio. PWEND [1] is an energy-efficient protocol. Among these works, RCI-SBA [30], the passive protocol [2] and PWEND [1] present an energy-aware mechanism, KPND [20] is implemented in MobiSim, although NS-2 and Matlab are used to simulate other recent protocols. Moreover, most of the recent protocols are suitable to be used in MANET environments.

In this paper we present an energy-aware randomized proposal to be used in static multi-hop wireless ad hoc environments, which takes into account the existence of collisions. It also aims at reducing the energy consumption in comparison to existing solutions.

3 Energy-aware Randomized Proposal based on Collision Detection

In this section, we proceed to present LECDH, an energy-aware randomized protocol.

3.1 Assumptions

The assumptions that our protocol has to consider include: The time is divided into slots and every node know the slot width, the nodes cannot move throughout a given area, each node holds a unique identifier. The identifiers do not need to be consecutive numbers, the nodes are randomly placed in an area, synchronization is necessary in slot boundaries, the number of nodes is not known by any node. Each node has a radio transceiver with limited transmission range, the transceivers of all the nodes have identical transmission range, and it allows half-duplex operation. Each node includes a memory to save local topology information, i.e., a neighbor table, collisions may appear, the nodes can detect collisions and termination. The nodes must be allowed to start transmitting at different time moments, and each node is powered by batteries.

In Table 1 more information about our LECDH proposal can be found.

Table 1 Qualitative comparison of EAH and LECDH.

	[3]	LECDH
Static environment	✓	✓
Mobile environment		
Randomized protocol	✓	✓
Slotted time	✓	✓
N remains unknown	✓	✓
Requires synchronization in slot boundaries	✓	✓
Does not follow a schedule	✓	✓
Transmitting/listening (not simultaneously)	✓	✓
One-hop scenario	✓	✓
Multi-hop scenario	✓	✓
Sleep mode available	✓	✓
Collisions are considered	✓	✓
Packet loss detection		
Leader needed		
Collision detection		✓
Termination detection		✓
Start transmission at different time instants	✓	✓
Discovers all neighbors almost with probability 1		✓
With feedback mechanism		✓

3.2 Model

In LECDH, time is slotted in rounds of size ω_t as shown in Figure 1, and each node can be in `Transmit`, `Listen`, `Sleep` or `Success` states, as shown in Figure 2, the state machine for LECDH that shows how our protocol operates. State `Success` means that the node already transmitted successfully, and it remains in this state until the algorithm ends.

The slot width ω_t takes a fixed value, not depending on the knowledge of the number of nodes N. This value must be properly chosen since this decision will affect to the performance of the protocol. A low value of ω_t may produce an improvement in the performance of small networks while worsen the performance of large networks; otherwise, i.e., a great value of ω_t may produce an improvement in the performance of large networks and the performance can worsen for small networks.

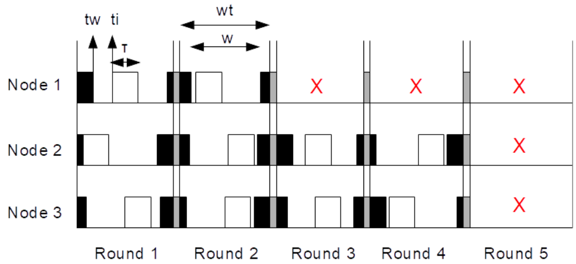

Fig. 1 LECDH protocol (timeline).

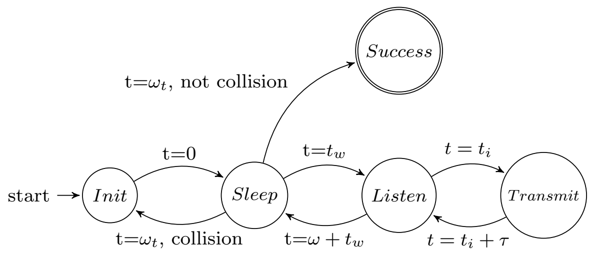

Fig. 2 LECDH state machine.

First, as shown in Figure 2, Figure 3 and Algorithm 1, `Sleep` state begins and the node keeps in this state during an independently and randomly chosen time t_w so that $0 \leq t_w \leq s$, being s the total sleep time in a round and it depends on ω_t and the DC (duty cycle), i.e., the percentage of time that the node is active. During t_w no messages are received since the node is asleep, and t_w is independent among nodes in a given round and independent among rounds in a given node. This situation can be seen in Figure 1 with black squares at the beginning and at the end of the round. The round duration is ω_t while the active period that includes listening and transmission has a width of $\omega = \omega_t \times DC$, being DC the duty cycle, and the total sleep time in a round is $s = \omega_t - \omega$. A node keeps in state `Sleep` at the beginning of the round during a time $t_w \in [0, s]$ and at the end of the round during a time $s_2 = s - t_w$.

After this sleep period t_w, if a node is not in `Success` state in that round, the node keeps in state `Listen` and randomly chooses a time t_i, so that $t_w \leq t_i \leq t_w + \omega - \tau$.

Then the node sends a single BROADCAST packet in that round starting in t_i during a time τ, which means that this node is in `Transmit` state, and then remains in the `Listen` state, i.e., listening for incoming

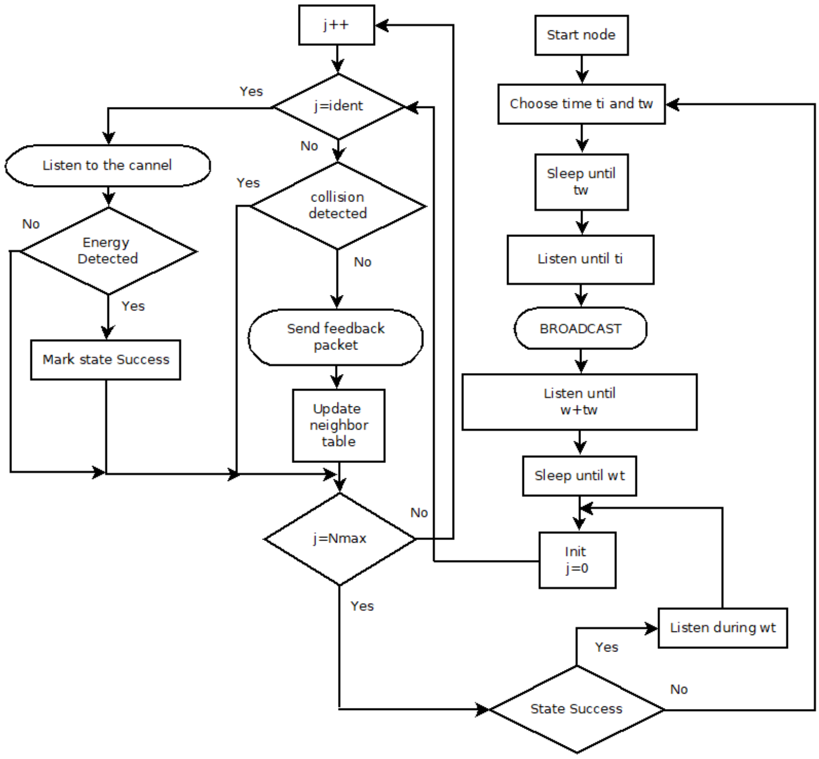

Fig. 3 LECDH flow diagram.

messages during $\omega - (t_i - t_w) - \tau$. The BROADCAST packets must include the identifier of the sender node and will be transmitted successfully if during the duration of transmission all the destinations are in state `Listen`.

Finally, the node goes back to `Sleep` state and keeps in this state during $s - t_w$.

Otherwise, i.e., the node is in `Success` state in that round, circumstance which is signalled as a red X mark in Figure 1, it will remain in this unchanged state and it will keep listening for BROADCAST packets from others.

Moreover, collision detection is performed by all the nodes when they are listening. If a certain node achieves to transmit successfully, which means that a collision did not take place for the node, the rest of nodes which are within transmission range update their neighbor tables with the identifier of this node. A serial of feedback packets will be sent, in a second sub-slot of fixed width ω_f, that indicates which nodes transmitted successfully (feedback packet). The time a node is transmitting a feedback packet is τ_f. The number of packets is fixed, i.e., it allows to ignore the number of nodes that conforms the network, and must be properly set to be suitable for the case of large networks. This situation is shown in Figure 1 by light grey squares after the end of the round.

As shown in Figure 3, the feedback packets will be sent one after another from positions 0 to the maximum number of nodes in the network (Nmax). According to Figure 3 and Algorithm 1, the nodes will send the j_{th} feedback packet if their identifier is not equal to j and node j transmitted successfully while it remains listening to the channel if the identifier is equal to j. A feedback packet in the j_{th} position indicates that the node whose identifier is j transmitted successfully, whereas an absence of feedback packet indicates that the BROADCAST packet sent by the node whose identifier is j collided.

When the node with identifier j listens to the channel, it proceeds to perform energy detection. If energy is detected, the node with identifier j will change its state to `Success` in the beginning of the next round, remains in this state, and keeps listening until the algorithm finishes, meaning that it will not contend from that moment on, although it will keep sending the feedback packets when necessary. Otherwise, a collision occurred by the BROADCAST sent by node j, i.e., the j_{th} position does not include a feedback packet, and node j will contend in the following round.

The feedback packets sending process also requires that the nodes are synchronized in slot boundaries, and the feedback packets are transferred one after another when necessary. It is required that all the nodes send the j_{th} feedback packets simultaneously. So, it is

Algorithm 1 LECDH

Require: τ time a node is transmitting, DC duty cycle, ω_t (a fixed round duration), *ident* identifier
1: $\omega = \omega_t \times DC$
2: $s = \omega_t - \omega$
3: termination = false
4: **while** not termination **do**
5: Choose randomly $t_w \in [0, s]$ and begin Sleep mode.
6: Keep in Sleep mode during t_w seconds.
7: Choose randomly $ti \in [t_w, t_w + \omega - \tau]$
8: Keep in Listen mode until t_i.
9: Send BROADCAST(i) beginning in t_i during τ, Transmit state.
10: Keep in Listen mode during $\omega - (t_i - t_w) - \tau$.
11: Keep in Sleep mode until the end of the round (during $s - t_w$)
12: **for** every j **do**
13: **if** j == ident **then**
14: Listen to the channel.
15: Perform energy detection.
16: **else**
17: **if** node j transmitted successfully **then**
18: Send feedback packet.
19: Update neighbor table with identifier j.
20: **end if**
21: **end if**
22: **if** j detected energy **then**
23: Node j in Success state from now on (when the feedback process ends) and keeps listening until the end of the protocol, although it will send feedback packets when necessary in the following rounds.
24: **else**
25: New round (when the feedback process ends). Node j keeps contending in the following round.
26: **end if**
27: **end for**
28: **if** no BROADCAST was received in a fixed number of consecutive rounds **then**
29: termination = true
30: **end if**
31: **end while**

guaranteed that the feedback packets will produce the detection of energy. Furthermore, the feedback packets are much smaller than the BROADCASTs.

This protocol also presents a termination detection mechanism so that each node finds out whether all the nodes within transmission range have managed to transmit successfully, meaning that all these nodes are in state `Success`. For this purpose, each node must find out the lack of existence of signal in the channel in a fixed number of consecutive rounds, which means that no BROADCAST was received, since all the nodes that are in state `Success` do not send a single BROADCAST in each round. In this case, we conclude that all the nodes are in state `Success` and the protocol finishes.

Figure 1 also represents an example of operation of LECDH for a network consisting of 3 nodes in a one-hop scenario, i.e. all the nodes are within transmission range of all the others. In round 1, the message of node 2 is sent during the sleep period of nodes 1 and 3 while the messages that are sent by nodes 1 and 3 overlap in time provoking a collision, thus all 3 nodes go on contending in the following round. In round 2, only node 1 manages to transmit successfully, thus it will not contend from now on, as indicated by a red X mark that appears in the following rounds, while the messages of nodes 2 and 3 provoke a collision, thus they go on contending in the following round. In round 3 a collision also takes place between nodes 2 and 3. In round 4 both remaining nodes managed to transmit successfully, and in round 5, it is proved that all the nodes have already managed to transmit successfully, therefore the protocol finishes.

Algorithm 1 shows how the LECDH proposal operates, including the equations to obtain ω, and s. Notice that it highlights the different operations in each state, the energy detection process and the steps to follow when there is a successful transmission or a collision. Moreover, in Algorithm 1 we use a fixed ω_t, that does not depend on N. In line 28, the termination condition checking is carried out.

4 Performance comparison

In this section a qualitative and quantitative comparison of our proposal against a reference protocol, will be presented.

4.1 Qualitative comparison

We have selected a randomized algorithm and used it as reference, i.e., the EAH protocol [3] for comparison purposes, since it is similar to our proposal LECDH.

Table 1 highlights the main characteristics of the reference protocol and our proposal. Table 1 shows that EAH is randomized, time is slotted, it only requires the nodes to be synchronized in slot boundaries, it may be used in one-hop and multi-hop environments, and it is one-way, although it does not succeed at discovering all the neighbors with probability 1. On the other hand, our LECDH proposal is randomized, time is also slotted, it also requires synchronization in slot boundaries, it achieves a discovery probability almost 1, the number of nodes remains unknown by all the nodes in the network, its use is possible both in one-hop and in multi-hop networks, sleep mode is available, collision and termination conditions are detected, it allows the nodes to start transmission at different time moments, and it is handshake-based, i.e. it includes a feedback mechanism.

4.2 Simulation setup

For both LECDH and EAH protocols, we varied the number of nodes N (scalability), and also the DC (Duty Cycle). To carry out our simulations we chose Castalia 3.2 [10].

The results have been obtained using the additive interference model (most realistic) for collisions, i.e., the parameter `collisionModel` set to 2 in Castalia 3.2.

To compare both protocols we consider a particular case setting the slot width to $\omega_t = N \times \tau$, an active period of $\omega = \omega_t \times DC$ and a sleep period of $s = \omega_t - \omega$. Furthermore, the time a node is transmitting has been set to $\tau = 0.07s$, i.e., setting ZigBee as radio model, and this value is identical for both protocols.

We consider two deployment areas of (i) 10m x 10m, i.e., one-hop setting, which is a simpler but useful scenario especially in those cases in which the transmission power of the transceivers is high, and (ii) 100m x100m multi-hop scenario, a more realistic scenario for devices that have limited transmission range radio transceivers. In our case, we organized N nodes in $M \times M$ grids.

We focus on the following metrics: the Discovery Time, the Number of Discovered Neighbors, the Energy Consumption (since LECDH is an energy-aware protocol), the Throughput, and the Discoveries per packet sent.

For EAH we set $0.5 \cdot N$ rounds in the one-hop setting and $0.25 \cdot N$ rounds in the multi-hop scenario. As for our proposal LECDH, it does not need to set a number of rounds, since it finishes when all the neighbors have been discovered.

For the experiments carried out, we used ZigBee (CC2420) radio model, setting the transmission power to -5dBm, the packet rate to 5 packet/s and the packet size to 2500 bytes.

In Table 2, we summarize the parameters set in the simulations.

Table 2 Simulation parameters.

Parameter	Value
Static	True
Radio model	CC2420
Collision model	2
Transmission power	-5dBm
Packet rate	5 packet/s
Packet size	2500 bytes
Feedback packet size	14 bytes
Slot width	$\omega_t = N \cdot \tau$
Feedback slot width	$\omega_f = N \cdot \tau_f$
Time a node is transmitting BROADCAST (τ)	0.07 s
Time a node is transmitting feedback packet (τ_f)	0.000392 s
One-hop size	10mx10m
Multi-hop size	100mx100m
Deployment	Grid MxM
EAH number of rounds (one-hop)	$0.5 \cdot N$
EAH number of rounds (multi-hop)	$0.25 \cdot N$
DC	40%-100%

4.3 Simulation results

Next, we carry out a performance comparison of our proposal against that for the reference protocol EAH.

4.3.1 Energy consumption

Figure 4 shows that LECDH, in the one-hop case, outperforms the reference protocol EAH for duty cycles 90% and 100%. LECDH performs worse when the duty cycle is reduced since more time is needed to discover all the neighbors, thus the energy consumption increases. When the duty cycle for EAH goes down the energy consumption is improved since EAH has a fixed number of rounds, thus the active period will decrease and the energy consumption is better. Moreover, the energy consumption for both protocols increase with the number of nodes. LECDH follows this trend since as the network gets more dense more collisions appear thus to discover all the neighbors the discovery time and the energy consumption increases, while EAH follows this trend as the discovery time depends on N, thus the energy consumption increases.

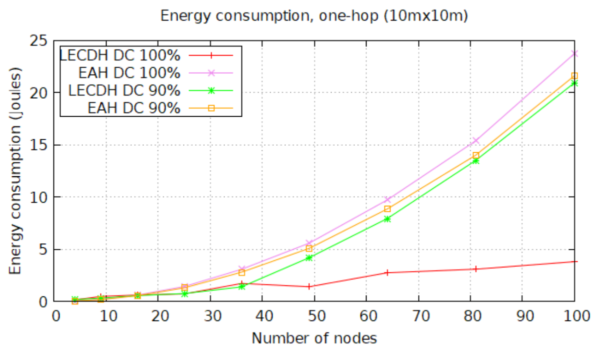

Fig. 4 Energy consumption comparison, (one-hop).

Figure 5 shows that, in the one-hop case, EAH outperforms LECDH for duty cycles 60%, 70% and 80%. Thus there is a duty cycle in which LECDH stops outperforming EAH. Again, as the duty cycle for LECDH is reduced, the energy consumption increases, since the protocol needs more time to discover all the neighbors thus it needs to spend more energy. Again, the energy consumption for both protocols increases as the network gets more dense, for the same reason stated above.

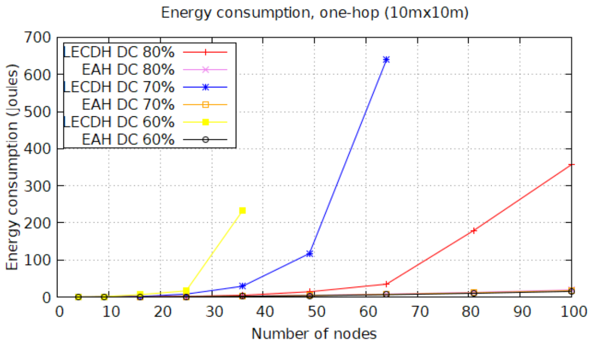

Fig. 5 Energy consumption comparison (one-hop).

As shown in Figure 6, in the one-hop case, when the duty cycle is greater or equal to 80%, LECDH performs worse than EAH for a number of node below 16, while LECDH performs better for number of nodes above 16 for duty cycles 100% and 90%. When the duty cycle for EAH is lower the energy consumption is better since EAH has a fixed number of rounds, thus this is true but the number of discovered neighbors will decrease. Moreover, for our LECDH proposal when the number of nodes is below 9, the energy consumption is reduced as the DC decreases, as expected. Furthermore, the EAH also should have increased energy and discovery time if the number of rounds had not been fixed to that value.

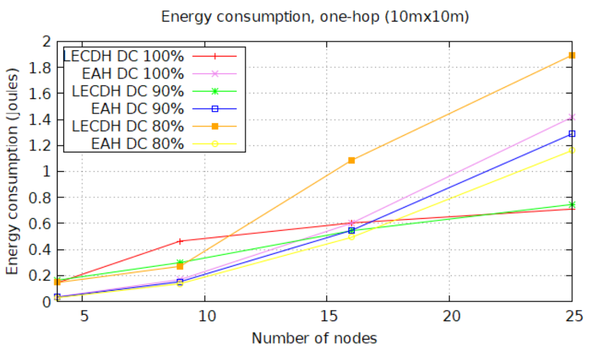

Fig. 6 Energy consumption comparison, 25 nodes (one-hop).

Figure 7, in the multi-hop case, shows that our proposal outperforms the reference protocol for duty cycles 80%, 90% and 100%, and both protocols follow an increasing trend for the reason stated above. Moreover, when the duty cycle is reduced the proposal performs worse since the time needed to discover all the neighbors increases, thus more energy is spent. As for EAH, as the duty cycle is reduced, the energy consumption is improved since this protocol has a fixed number of rounds thus the active period is reduced and the energy consumption is also reduced.

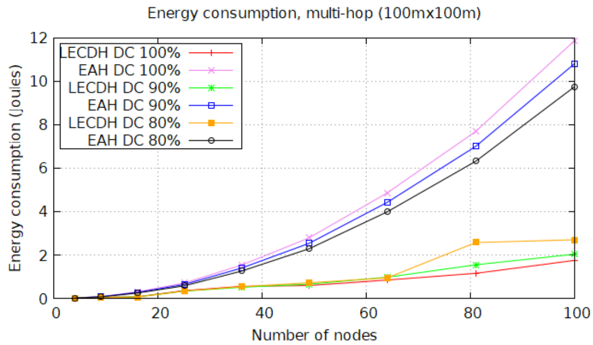

Fig. 7 Energy consumption comparison, (multi-hop).

Figure 8 shows that, in the multi-hop case, LECDH outperforms EAH when the duty cycle is 70%, while it presents worse results than EAH for duty cycles 50% and 60%, since the number of rounds for EAH is fixed, while LECDH needs more time to discover all the neighbors, thus more energy is spent. Notice that there is a DC in which LECDH stops outperforming EAH. In addition, for the EAH, as the DC decreases the energy consumption improves (for a fixed number of rounds). As for the LECDH, as the DC decreases, the energy consumption grows, since it requires more time to discover all the neighbors, thus more energy is spent. For both protocols, the energy consumption increases as the number of nodes grows for the reason stated above.

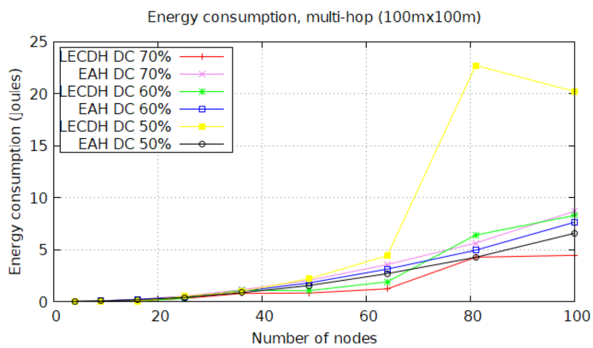

Fig. 8 Energy consumption comparison, (multi-hop).

As for the LECDH, in the multi-hop case, for duty cycles 40%-100%, as shown in Figure 9, for a number of nodes below 16, when the DC decreases the energy consumption is improved, as expected. However, this behavior does not take place for number of nodes above 16.

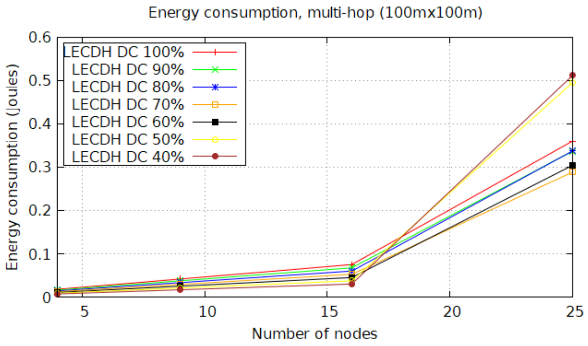

Fig. 9 Energy consumption comparison, 25 nodes (multi-hop).

4.3.2 Discovery Time

For the EAH, we set the number of rounds to the same value for all the duty cycles, thus the discovery time will be the same no matter which duty cycle is set.

Figure 10 shows that, in the one-hop case, LECDH outperforms the reference protocol when the DC is 90% and 100%, while when the DC is reduced for our LECDH the discovery time is increased, since more time is needed to discover all the neighbors. However, the discovery time is the same in EAH for both duty cycles, since the number of rounds is fixed. Furthermore, the discovery time for both protocols increases as the number of nodes grows, for the same reason stated above for the energy consumption.

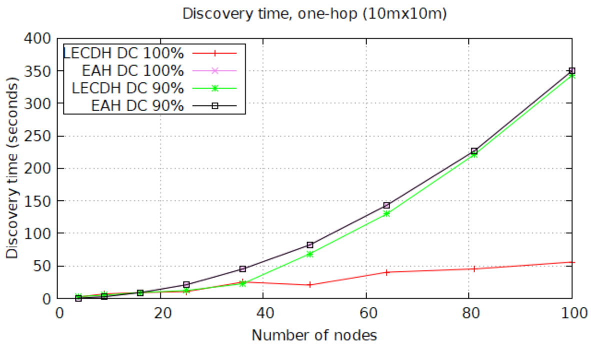

Fig. 10 Discovery Time comparison, (one-hop).

As shown in Figure 11, in the one-hop case, for LECDH when the duty cycle is reduced better discovery time is obtained for number of nodes below 9, as expected. EAH is better than the proposal when the number of nodes is below 16, whereas LECDH outperforms the reference protocol when the number of nodes is above 16, except for the DC 80% case. Furthermore, the discovery time in the reference protocol is the same for any duty cycle, since the number of rounds is fixed.

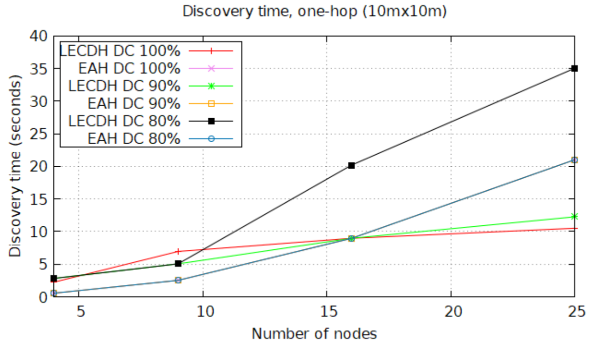

Fig. 11 Discovery Time comparison, 25 nodes (one-hop).

Figure 12 shows that, in the multi-hop case, for our proposal as the duty cycle is decreased the discovery time increases, since more time is needed to discover all the neighbors. LECDH is better than EAH when the duty cycle is from 70% to 100%, whereas EAH is better when the DC is lower than 60%. Therefore, there is a given DC in which LECDH stops performing better than EAH. The discovery time is the same for the EAH no matter which DC is set since the number of rounds takes a fixed value. The discovery time also presents an increasing trend with the number of nodes for both protocols. This is because in LECDH as the number of nodes gets higher more collisions take place thus the time to discover all the neighbors increases. As for EAH the discovery time depends on N thus the time also increases.

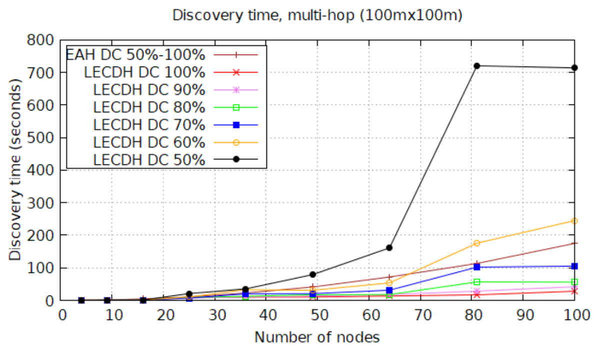

Fig. 12 Discovery Time comparison, (multi-hop).

In Figure 13, in the multi-hop case, the simulation results for networks composed of less than 25 nodes are presented. LECDH outperforms EAH for number of nodes below 17, while the EAH presents the same results for all the duty cycles since the number of rounds is fixed. However, the discovery time for LECDH increases when the duty cycle is reduced for number of nodes above 16, since the protocol requires more time to discover all the neighbors.

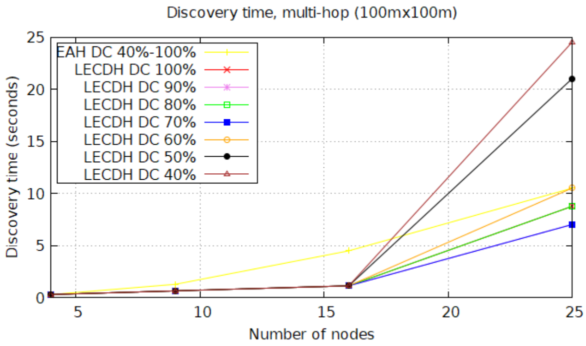

Fig. 13 Discovery Time comparison, 25 nodes (multi-hop).

4.3.3 Number of discovered neighbors

As for a one-hop scenario, as shown in Figure 14, our proposal outperforms the reference protocol. In addition, the results of LECDH for the different duty cycles is the same, since our LECDH protocol manages to discover all the neighbors no matter which duty cycle we set. Furthermore, for the EAH, in which we set a fixed value, i.e., the same number of rounds, for all the duty cycles, as the DC decreases the number of discovered neighbors also decreases, as expected. However, the EAH does not succeed at discovering all the neighbors.

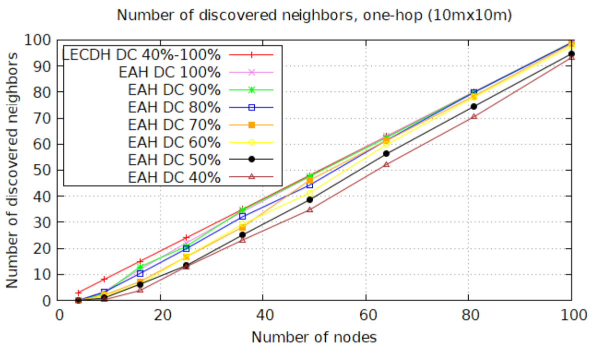

Fig. 14 Number of discovered neighbors comparison, (one-hop).

According to Figure 15, in a multi-hop scenario, LECDH outperforms EAH for all the duty cycles, and manages to discover all the neighbors. Furthermore the number of discovered neighbors for the EAH gets lower as the duty cycle decreases, as expected, since we have set a fixed number of rounds for EAH. However, again the EAH does not succeed at discovering all the neighbors.

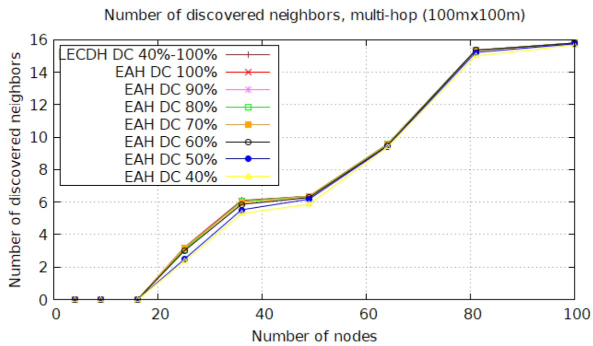

Fig. 15 Number of discovered neighbors comparison, (multi-hop).

According to Figure 16, in the multi-hop case for low number of nodes, our LECDH proposal outperforms EAH, and manages to discover all the neighbors. In addition, for the EAH, having set a fixed number of rounds for the different duty cycles, as the DC decreases, the number of neighbors discovered gets lower, as expected. Moreover, the reference protocol does not succeed at discovering all the neighbors.

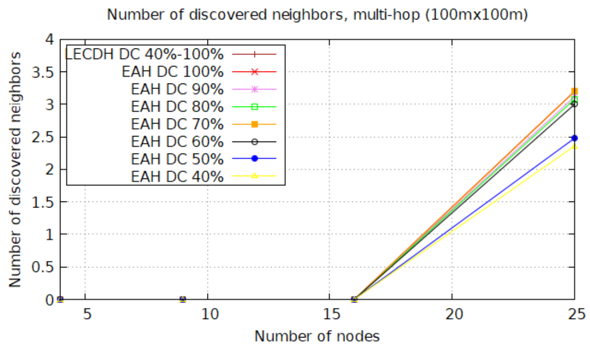

Fig. 16 Number of discovered neighbors comparison, 25 nodes (multi-hop).

4.3.4 Throughput

Regarding the throughput metric in a one-hop scenario, and as shown in Figure 17, LECDH outperforms the reference protocol for duty cycles 70% to 100%. Furthermore, the throughput follows a decreasing trend with the number of nodes for LECDH, since more collisions occur, thus the number of packets received is lower and more time is required to discover all the neighbors. Moreover the throughput follows a decreasing trend for EAH since the time depends on N and the time grows thus the throughput will decrease as the number of nodes grows. However, for LECDH when the duty cycle is reduced, the throughput is worse, since the time is inversely related to the throughput and the protocol needs more time to discover all the neighbors.

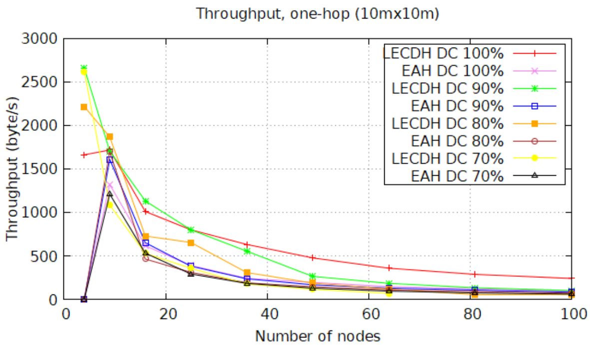

Fig. 17 Throughput comparison, (one-hop).

As shown in Figure 18, in the one-hop case, for DC 70% to 100%, and a number of nodes below 25, our proposal also outperforms the reference protocol regarding the throughput.

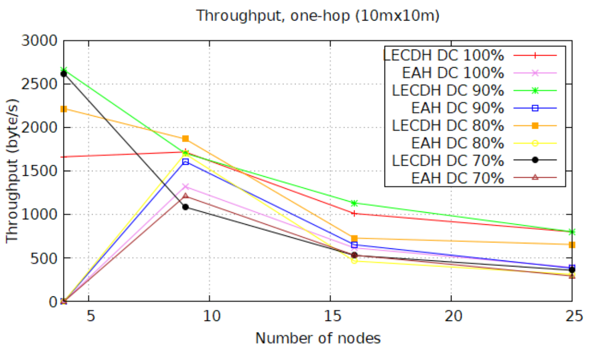

Fig. 18 Throughput comparison, 25 nodes (one-hop).

According to Figure 19, in the multi-hop case, LECDH outperforms EAH in terms of throughput for duty cycles 70% to 100%. Both protocols follow a decreasing trend for the same reason stated above. For LECDH, as the duty cycle is reduced worse results are obtained since more time is necessary to discover all the neighbors, thus the throughput is reduced.

Figure 20 shows that, in the multi-hop case, the proposal again outperforms EAH for duty cycles 40% to 60% regarding the throughput. Again, both protocols follow a decreasing trend for the same reason stated above. However, for LECDH as the duty cycle

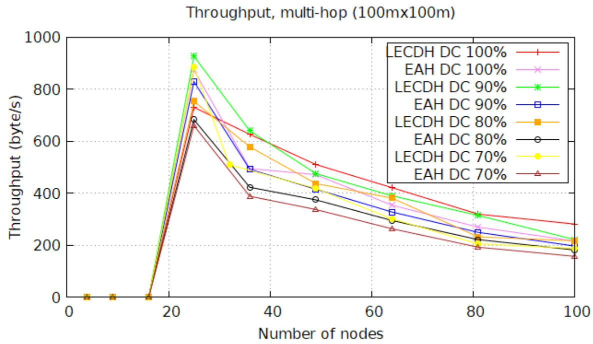

Fig. 19 Throughput comparison, (multi-hop).

is reduced the throughput is reduced, since more time is necessary to discover all the neighbors and time is inversely related to the throughput.

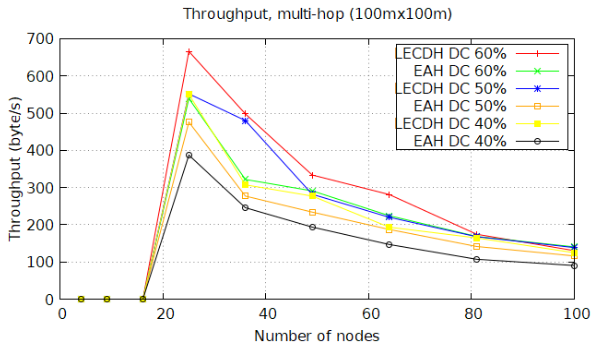

Fig. 20 Throughput comparison, (multi-hop).

4.3.5 Discoveries per packet sent

According to Figure 21, for the one-hop case, the proposal outperforms EAH for duty cycles 90% and 100%, although EAH with DC 80% outperforms the proposal for networks composed of more than 36 nodes. Therefore, there is a DC value in which LECDH stops outperforming EAH. However, as the duty cycle is reduced, LECDH performs better for a number of nodes below 10, as expected.

According to Figure 22, in the multi-hop case, regarding the discoveries per packet sent, LECDH outperforms EAH for duty cycles 80%, 90 % and 100%. However, as the duty cycle is reduced, LECDH presents worse results, since more time is necessary to succeed at discovering all the neighbors, thus more packets are sent to discover the same amount of neighbors.

5 Conclusion

This work addresses the neighbor discovery in the context of static multi-hop wireless ad hoc environ-

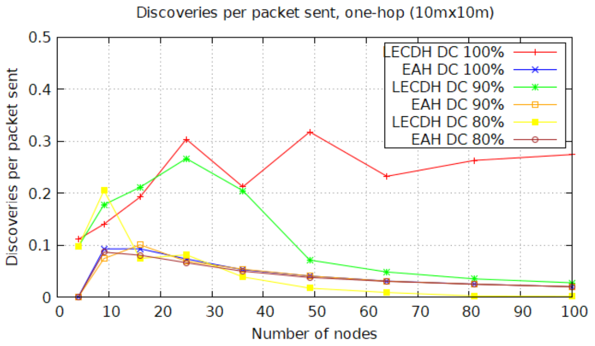

Fig. 21 Discoveries per packet sent, comparison (one-hop).

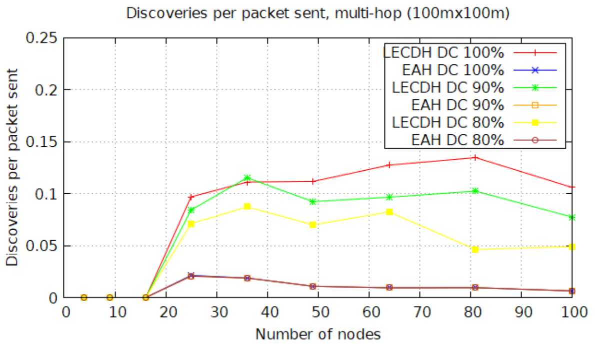

Fig. 22 Discoveries per packet sent, comparison (multi-hop).

ments considering the existence of collisions, and focusing on energy consumption.

A protocol from the literature has been chosen for comparison purposes and used as reference, i.e., EAH, and a randomized low energy consumption proposal LECDH, which takes the advantages of collision detection, has been presented. Both protocols have been simulated through Castalia 3.2 for comparison purposes, focusing on both one-hop and multi-hop neighborhood, using the energy consumption, the discovery time, the number of discovered neighbors, the throughput and the discoveries per packet sent metrics, and varying the duty cycle.

According to the simulation results, we conclude that LECDH improves the reference protocol in terms of the five metrics in both neighborhood environments for high duty cycles. Moreover, for LECDH in small networks, when the DC decreases, better results are obtained for all 5 metrics in both environments.

Overall, we found that LECDH operates following more realistic assumptions, such as it detects collisions and termination, succeeds at discovering all the neighbors almost with probability 1, allowing the nodes to start transmitting at any time moment, and the number of nodes can remain unknown.

Among its practical limitations, the LECDH requires nodes to be synchronized in slot boundaries, its use in MANETs is not allowed, and it is only appropriate for high duty cycles, i.e. below 40% the discovery time and the energy consumption increases exorbitantly.

As for the proposal, it can be applied in real-world environments, such as static wireless ad hoc networks with high duty cycles and composed of a low amount of nodes in one-hop or multi-hop environments, such as wireless sensor networks, in which the low energy consumption is a main goal to achieve.

As future directions we are interested in extending the protocol to solve the above limitations, propose a new low energy consumption protocol for the creation of spontaneous networks based on trust, and neighbor discovery protocols suitable for mobile environments.

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