Telecommunication Systems (2021) 77:577–596
https://doi.org/10.1007/s11235-021-00763-4

Randomized neighbor discovery protocols with collision detection for static multi-hop wireless ad hoc networks

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Accepted: 12 February 2021 / Published online: 27 March 2021

Abstract
Neighbor discovery represents a first step after the deployment of wireless ad hoc networks, since the nodes that form them are equipped with limited-range radio transceivers, and they typically do not know their neighbors. In this paper two randomized neighbor discovery approaches, called CDH and CDPRR, based on collision detection for static multi-hop wireless ad hoc networks, are presented. Castalia 3.2 simulator has been used to compare our proposed protocols against two protocols chosen from the literature and used as reference: the PRR, and the Hello protocol. For the experiments, we chose five metrics: the neighbor discovery time, the number of discovered neighbors, the energy consumption, the throughput and the number of discovered neighbors versus packets sent ratio. According to the results obtained through simulation, we can conclude that our randomized proposals outperform both Hello and PRR protocols in the presence of collisions regarding all five metrics, for both one-hop and multi-hop scenarios. As novelty compared to the reference protocols, both proposals allow nodes to discover all their neighbors with probability 1, they are based on collision detection and know when to terminate the neighbor discovery process. Furthermore, qualitative comparisons of the existing protocols and the proposals are available in this paper. Moreover, CDPRR presents better results in terms of time, energy consumption and number of discovered neighbors versus packets sent ratio. We found that both proposals achieve to operate under more realistic assumptions. Furthermore, CDH does not need to know the number of nodes in the network.

Keywords Wireless ad hoc networks · Neighbor discovery · Collision detection · Randomized protocols · One-hop · Multi-hop

1 Introduction

Wireless ad hoc networks present a lack of communication infrastructure right upon their deployment, and the nodes that conform them are equipped with limited range radio transceivers [1, 2].

Therefore, while some destination nodes can be reached directly (known as one-hop neighbors), other nodes require multiple intermediate nodes to communicate in a multi-hop fashion, and thus each intermediate node must be able to act as a router by forwarding data not addressed to its own use [3, 4].

The main problem in wireless ad hoc networks is that, right after the deployment, the nodes do not know which are their neighbors, and what is the number of neighbors. So, the nodes must have the ability to self-configure to establish a communications infrastructure, and also gain awareness about the neighbors (i.e., the nodes within their transmission range). In other words, to overcome this problem, Neighbor Discovery techniques must be developed, and they are introduced as a first step after node deployment [5, 6].

Overall, wireless ad hoc networks can be: (1) static, e.g., mesh networks or sensor networks, when nodes are thrown from a plane to a forest [7], or (2) mobile, e.g., mobile robots equipped with radio transceivers [8].

On the other hand, Neighbor Discovery algorithms can be classified as (1) randomized and (2) deterministic. In the

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randomized approaches each node randomly chooses a state either transmitting or listening in each time slot (round), or transmits at a randomly chosen time instant, and manage to discover all its neighbors in a given time with a high probability. As for the deterministic protocols, the nodes transmit according to a predetermined transmission schedule and allow them to discover all their neighbors in a given time with probability 1.

There are many application areas [9] that could benefit from wireless ad hoc networks, such as the industrial (e.g., sensor communications, robots and digital networks), business (e.g., meetings, stock control), military (e.g., tough and hostile environments), and education.

Many protocols in the literature, i.e., the deterministic approaches, need a transmission schedule for neighbor discovery, while some randomized protocols require non-realistic assumptions such as not knowing the termination condition of the neighbor discovery process or the lack of knowledge of the number of neighbors.

Therefore, the main objective of our work is to propose and evaluate randomized protocols which do not rely on a transmission schedule, cope with collisions, follow more realistic assumptions and obtain better performance than existing solutions.

In this paper we focus on neighbor discovery in static multi-hop wireless ad hoc networks, and present two randomized approaches that solve the neighbor discovery problem in the presence of channel collisions, phenomenon that takes place when two or more nodes try to transmit simultaneously, and take the advantages of collision detection.

Our proposals are compared against two existing approaches selected from the literature, which are used as reference: the Hello protocol [10], and the PRR (Probabilistic Round Robin) protocol [7]. For validation and comparison purposes, our proposals and both reference protocols have been implemented using the Castalia 3.2 simulator [11]. To evaluate these protocols, we relied on five performance metrics: the neighbor discovery time, the number of discovered neighbors, the energy consumption, the throughput and the number of discovered neighbors versus packets sent ratio.

The main problem found in existing protocols such as [10] and [7] is that they do not know when to terminate the neighbor discovery process and the neighbors are discovered with a high probability (different from 1). In addition, protocol in [7] needs to know the number of nodes in the network. Thus, we aimed at improving those protocols providing collision detection and termination conditions, allowing the protocol to operate without knowing the number of nodes, and obtaining better performance.

The problem statement we must face while proposing a neighbor discovery protocol is: the nodes must operate in static environments, they have limited range radio transceivers, half-duplex mode is available, nodes are randomly deployed in a given area, nodes should be asynchronous, channel collisions may occur, nodes can detect collisions, the number of nodes in the network have to be unknown and the nodes must be able to start transmission at different time instants, the nodes must discover all their neighbors with probability 1 (if possible) and know when to terminate the discovery process when all the neighbors have been discovered, and obtain better performance than existing protocols.

Our work is different from recent works in the literature such as [12] which uses a Kalman filter as a prediction model, combines hello messages and node mobility prediction, and uses the ALOHA-like [2] mechanism with transmission probability 0.5, [13] that uses prior information from radars to accelerate the speed, integrates radar and communication, the protocol is 3-way but feedback might collide, and uses directional transmission and directional reception, [14] where the protocol combines routing and neighbor discovery, without having a priori knowledge of the network parameters (such as size, topology or mobility), [15] presenting a cross-layer protocol that performs neighbor discovery in the MAC layer, hello messages are sent periodically after a random backoff in a TDMA method, with the aid of hexagonal clustering and GPS to update the latest information of neighbors, [16] which uses directional antennas, and model neighbor discovery as a finite-state learning automaton, the protocol operates in a ALOHA-like manner, 2-way handshaking on the same beam where nodes transmit or receive with equal probability, [17] that integrates radar and communication, using directional antennas, making use of a two-way handshaking for each direction sending hello messages, in [3] neighbor discovery with social recognition under a passive discovery framework, broadcasts a wake-up radio signal before the hello message broadcast to trigger from idle to active modes, hello messages are integrated with social information, and neighbor discovery is performed in the MAC layer, [4] beacons are separated from active slots, a periodical broadcast of beacons can be dynamically adjusted to accelerate the discovery, and proactive wake-up is available. Most of these protocols are used in mobile environments.

The novelty of the proposals compared to prior recent works are: there are no radars nor directional antennas, the protocols are 2-way protocols using omnidirectional radio transceivers, a schedule is not used, neighbor discovery is performed at the routing layer, a priori knowledge of the network parameters is not required in CDH but it is necessary in CDPRR, and the protocols are designed to be used in static environments.

The main contributions of this work are: (i) CDH (Collision Detection Hello), a randomized proposal based on collision detection and Hello protocol with fixed slot width that achieves to discover all the neighbors with probability 1, terminating when all the neighbors have been discovered, following more realistic assumptions, such as not knowing the number of nodes in the network, it can transmit at different time instants, and it is suitable to be used both in one-hop and multi-hop scenarios, (ii) CDPRR (Collision Detection Probabilistic Round Robin), a randomized protocol based on collision detection and PRR protocol with a fixed transmission probability $\frac{1}{N}$ during all the neighbor discovery process which achieves to discover all the neighbors with probability 1, terminating when all the neighbors have been discovered, although it requires to know the number of nodes in the network, and it is suitable to be used both in one-hop and multi-hop scenarios, (iii) a qualitative comparison of the related work protocols and the proposals, (iv) implementation of both proposals and the reference protocols in Castalia 3.2 simulator [11] to obtain results regarding time, number of discovered neighbors, energy consumption, throughput and the number of discovered neighbors versus packets sent ratio. Furthermore, we found that the proposals are faster, and more energy efficient than the existing protocols.

The rest of this paper is organized as follows: A brief related work is discussed and a qualitative comparison of our proposals against recent existing protocols are included in Sect. 2. Our approaches, system overview, assumptions and models can be found in Sect. 3, while an overview of the reference protocols, the simulation setup and the results obtained through simulation are presented in Sect. 4. Finally, some concluding remarks and future research work are made in Sect. 5.

2 Related work

In the literature, many works that deal with the neighbor discovery problem can be found, some of them are discussed below and a qualitative comparison of these protocols is presented in this section.

In the context of static wireless ad hoc networks, a protocol that saves energy during deployment, and that efficiently performs neighbor discovery, is described in [7]: A probabilistic analog of the deterministic round robin scheduling algorithm, the PRR (Probabilistic Round Robin). PRR is able to maximize the probability of neighbor discovery. Its main drawback is that, in dense networks containing many neighbors, the protocol may fail to discover some of them. The authors also present the family of probabilistic protocols known as Birthday protocols.

A study of the impact of collisions and interference on a neighbor discovery process in the context of static multi-hop wireless networks is described in [10]. Two similar protocols, known as Basic Hello protocol and Energy-aware Hello protocol are presented, the latter one manages to reduce energy consumption.

In [10], three radio models have been described, in which both interference and collisions have been handled in very different ways.

The PRR and Basic Hello protocols are used as reference for comparison purposes in Sect. 5, and a more in-depth description about them can be found in Sect. 3.

According to [2], the authors present several randomized contributions for static networks, along with their resulting complexities which depend on the assumptions considered. First, a one-hop network of n nodes, known as ALOHA-like algorithm, where each node discovers all its neighbors in $O(n \ln n)$, is presented. Then, the authors present a protocol that is order-optimal in the one-hop case, and that allows each node to discover all its neighbors in O(n). The absence of an estimate of the number of neighbors n or the lack of synchronization among nodes, results at most in a slowdown of no more than a factor of two in the algorithm performance, compared to when nodes know n or when nodes are synchronized. Furthermore, some of the proposed algorithms allow nodes to begin execution at different time instants, and to terminate neighbor discovery after discovering all their neighbors. An extension to a general multi-hop wireless network setting is also available, which outperforms the ALOHA-like algorithm.

A synchronous full duplex neighbor discovery protocol, called FRIEND, for static networks is presented in [18]. The authors describe a randomized pre-handshaking protocol, although they also deal with half-duplex communications, multi-hop scenarios, and duty cycled networks. According to the results obtained through mathematical analysis and simulation, the protocols in [18] decrease the duration of neighbor discovery by up to 68% in comparison to the classical ALOHA-like protocols presented earlier [2].

Two practical and scalable detection algorithms developed from the group testing viewpoint for static networks, known as Direct Algorithm and Group Testing with Binning, are presented in [19]. The complexity of the Direct Algorithm is $O(k(\log k)^2 \log\log k)$. Although it performs well as the total number of nodes becomes large, its computational complexity can be improved. For this purpose, an efficient solution known as Group Testing with Binning is proposed. The resulting complexity of Group Testing with Binning is $O\left(\left\lceil \frac{1}{\beta} \right\rceil \max\left\{k^{\beta}(\log k^{\beta})^2 \log\log k^{\beta}, \left\lceil k^{1-\beta} \right\rceil\right\}\right)$, although a system can be designed such that k^{β} is a constant with complexity $O(k \ln k)$. A comparison of these approaches with randomized protocols similar to the Birthday-listen-and-transmit algorithm [7] was made in [19], showing that both algorithms (Direct Algorithm and Group Testing with Binning) achieve high discovery accuracy, and are much faster than the existing randomized protocols.

A prime-set based probabilistic algorithm for low duty cycle mobile WSN (Wireless Sensor Networks), called PSBA, is presented in [20]. According to PSBA, each node randomly chooses a prime p from a prime set, which is related to the duty cycle, and uses it as a schedule. The node will wake up every p slots in a cycle. Using PSBA, the typical long tail of the probabilistic algorithms can be improved, the average discovery latency and the energy consumption can be reduced in comparison to existing algorithms. The authors in [20] found that PSBA outperforms the Birthday protocol [7] regarding the average latency when the duty cycle is set to 1%, and the long tail of this protocol is improved. Furthermore, PSBA also improves Birthday, Disco [21] and SearchLight [22] protocols in terms of average latency when the duty cycle is from 1 to 5%. However, PSBA is tailored to low duty cycle dynamic WSNs. Moreover, the authors found that the lower the duty cycle, the better the PSBA performance, compared to existing algorithms.

In [23], a Power Aware Neighbor Discovery Asynchronous protocol, also known as Panda, is presented as a generalized probabilistic protocol, and it is the first neighbor discovery protocol for EH (Energy Harvesting) nodes. A version of this protocol is also available in [23], called Panda-D, which extends the protocol to work well under scenarios with non-homogeneous power harvesting, hence following more realistic assumptions. The authors found that for a high power budget, the discovery latency decreases.

Panda outperforms the low-power SearchLight-E (SearchLight [22] for power budget) and low-power BD-E (Birthday [7] for power budget) protocols by more than × 3 in terms of average discovery rate. Moreover, Panda outperforms the worst-case discovery latency bound of SearchLight-E protocol by up to 40%.

Panda and Panda-D have similar energy consumption and discovery rates when the nodes remain in a one-hop setting with homogeneous power budgets. However, in a multi-hop topology, the discovery rate between nodes is within 1% of the analytical discovery rate for a one-hop network. There is an implementation of Panda available in a unique EH ultra-low-power node prototype, based on the TI eZ430-RF2500-SEH. A remarkable result is that Panda is highly practical and can be applied to nodes with a non-rechargeable battery, where the power budget is set based on the desired lifetime.

Nihao [24] is an energy-efficient asynchronous protocol for symmetric and asymmetric scenarios. In [24], the first work that considers channel occupancy and use the duty cycle, latency and channel occupancy rate (COR) product metric, is presented. A version, S-Nihao (Simplified Nihao), leaves only one wake-up slot in a schedule cycle, guaranteeing bidirectional discovery. Analytical results suggest that S-Nihao is better than the LL-Optimal (Combinatoric) [25] schedule, given a specific duty cycle, with a lower latency bound. S-Nihao greatly outperforms existing discovery protocols when only the duty cycle and the latency are taken into account (× 10 better with duty cycle 5%, and × 50 better with duty cycle 1%). The main drawback of S-Nihao is that there may be a great amount of collisions if a node is surrounded by many neighbors. G-Nihao (Generic Nihao) is the first protocol to consider COR in neighbor discovery, a parameter that can be flexibly adjusted. G-Nihao guarantees the discovery and presents a good duty cycle granularity in the asymmetric case. The B-Nihao (Balanced Nihao) is most suitable for practical applications in the symmetric case. Nihao has been implemented on TinyOS 2.1.2 and an IEEE 802.15.4-compatible radio. According to experimental results, B-Nihao is significantly faster than Birthday [7], Disco [21], U-Connect [26] and SearchLight [22], for both duty cycles of 1% and 5% with the lowest latency bound. G-Nihao is faster than Disco, U-Connect, SearchLight and BlindDate [27], for duty cycles of 1% and 5%, since it has the lowest worst-case latency.

A gossip based neighbor discovery algorithm and a novel routing algorithm for MANETs that use smart directional antennas to optimize energy consumption is presented in [28], and it can be found in Springer Telecommunication Systems. Two protocols have been proposed, one of them aiming at increasing the number of discovered neighbors taking into account the nodes that are located in the second-hop, whereas the other one aims at reducing the number of hops in a route between source and destination nodes, which can be achieved taking the advantage of directional antennas. A four-way handshake mechanism is performed where the nodes use the antenna sector to discover each other. The protocol also assumes that nodes are synchronized, and a search is performed sequentially.

The simulation results obtained through Matlab, show a reduction in the time consumption and an increase in the throughput compared with other reactive routing protocols.

As a summary, Table 1 presents a qualitative comparison of the different neighbor discovery protocols discussed so far.

According to Table 1, all the protocols presented so far are tailored for static networks except for [28] and time is slotted, most of them are randomized, the protocols are asynchronous except for [18, 19] and [28] which require synchronization, they are designed to be used in multi-hop environments except for [7] and [19] which can only be used in a one-hop scenario, N is unknown for [2, 10, 20] and [23], while full duplex and pre-handshaking are required in [18] and group testing is used in [19].

Next, some more recent neighbor discovery works will be discussed.

A fast and efficient protocol KPND (Kalman Prediction-based Neighbor Discovery) for neighbor discovery in highly dynamic scenarios, based on a novel mobility prediction model using Kalman filter theory and hello messaging is

Table 1 Qualitative comparison of related work protocols

	[7]	[10]	[2]	[18]	[13]	[20]	[23]	[24]	[28]
Mobile network	No	No	No	No	No	No	No	No	Yes
Time slotted	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Randomized	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Asynchronous	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
One-hop	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Multi-hop	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
N unknown	No	Yes	Yes	No	No	Yes	Yes	No	No
Handle collisions	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Full duplex	No	No	No	Yes	No	No	No	No	No
Pre-handshaking	No	No	No	Yes	No	No	No	No	No
Group testing	No	No	No	No	Yes	No	No	No	No

proposed in [12]. It uses GPS devices, it takes into account temporal and spatial movements of nodes, movement trajectory information is used, and it detects the arrival and departure of neighbors.

Simulations have been performed through NS3.28 and Mobisim to obtain accuracy, robustness and efficiency.

According to the results, the KPND generally outperforms HP-AODV, ARH [29] and ROMSG [30]. The hello overhead of KPND is the smallest of the three protocols especially much smaller than HP-AODV. In KPND the number of hello messages are less than that of ARH and ROMSG. KPND can obtain higher accuracy rate compared with ARH. In comparison to HP-AODV, the accuracy rate of ARH, ROMSG and KPND are all much lower. KPND has the lowest error rate in contrast with the other three protocols.

Radar assisted fast neighbor discovery for wireless ad hoc networks is proposed in [13] for MTC (Machine-type communication). Four algorithms have been designed according to the feedback mechanisms and the accuracy level of prior information provided by the radar. Numerical results show that compared with algorithms without accurate prior information from the radar, the time consumption of the protocol is reduced with the prior information from the radar. According to simulation results, the authors found that when the number of beams and the number of neighbors are the same, the largest probability of discovery can be achieved, and also found that the time consumption with prior information from the radar increases with the number of nodes.

Moreover, the authors found that both the stop-discovery mechanism and the non-response mechanism can speed up neighbor discovery process, while the increasing speed is much slower without prior information from the radar.

Furthermore, the proposal outperforms the CRA (Completely random algorithm) [31] regarding time consumption.

However, integration of radar and communication is required, and the nodes assume synchronization and half-duplex mode.

A neighbor discovery protocol with distributed network control suitable for MANETs and an integrated protocol combining routing, scheduling and network/neighbor discovery are presented in [14]. The protocol uses modified versions of AODV and CSMA to perform blind route discovery and forwards packets simultaneously performing network/neighbor discovery, it focuses on highly dynamic resource constrained MANETs, and neither GPS nor other outside knowledge of node location, or mobility is required.

Simulation results show that the proposal performs well even without a priori knowledge of the network parameters.

Furthermore, the results show that both the completeness and accuracy of the network estimate improve as time passes. As the number of neighbors decreases, the accuracy increases while the time until a complete estimate is obtained increases.

Moreover, the protocol is robust against node mobility, failure or node joining the network in a variety of network configurations.

A cross-layer neighbor discovery algorithm, called ND_HC, is proposed in [15] to perform the neighbor discovery in the MAC layer, which combines TDMA and network clustering with GPS to determine the neighbors.

The hello messages are produced in the MAC layer and sent periodically after a random backoff time in TDMA method with the help of regular hexagonal clustering for large-scale wireless networks to improve the performance, and GPS devices are used to obtain accurate location information and keep the clock synchronized. This method reduces the packet collision probability and improve the throughput in the network. The protocol takes the advantages of both TDMA (which provides contention free transmission and reduces the collisions) and CSMA.

Simulation results have been obtained through NS-2 and show that compared to the traditional neighbor discovery algorithm in IEEE802.11 (ND_802.11), the proposal improves the efficiency of neighbor discovery, and obtains stable delay bounds.

ND_802.11 leads to more waste of network resources than ND_HC, whereas ND_HC is capable of finding 65% of its neighbors and ND_802.11 can find 30% of its neighbors.

In conclusion, compared with traditional neighbor discovery algorithm in IEEE 802.11, the proposal is more effective for finding neighbors in terms of the ratio of neighbors found per cycle and the time cost for finding all neighbors.

In [16], neighbor discovery is modeled as a learning automaton, operating in a non-stationary learning environment with unknown dynamics. The nodes learn about its environment from its past observations and adjust their strategy to achieve a faster discovery rate in dense networks.

A fully directional intelligent learning-based neighbor discovery scheme based on finite-state learning automata (FLA) is proposed in [16], in which each node is considered as an intelligent agent, it is clock synchronized, and it is equipped with a steerable directional antenna that allows the node to transmit or listen with equal probability in an ALOHA-like fashion, in one of the sectors. The protocol chooses the next sector by taking into account collisions and previously discovered neighbors which leads to a successful neighbor discovery with a high probability.

The automaton chooses an action and receives a reinforcement signal describing if reward or penalty is necessary.

Simulation results have been obtained to compare the performance of the proposal against the 2-way random handshaking algorithm [32] and the scan based algorithm [33].

Authors found that the learning automaton based scheme achieves a faster neighbor discovery rate. The proposal requires 48% fewer time slots to achieve 90% neighbor discovery compared to the random scheme and 68% fewer slots compared to the scan-based algorithm. In conclusion, the simulation results show that the use of the learning algorithm presents a significant performance improvement over existing random and scan based neighbor discovery schemes for different node densities and beamwidths. In addition, the proposal performs particularly well in networks with narrow beamwidth and high node density.

A novel energy efficient radar-communication integration enabled neighbor discovery scan based algorithm (RCI-SBA) [17] for ad hoc networks, which makes full use of the location information of neighbors provided by radar detection, aiming at reducing the energy consumption, and integrates the radar and communication, is proposed.

All the nodes are equipped with integrated directional antennas, radar signals and communication signals, the nodes maintain an antenna beam list, and each node forms a communication neighbor list.

A two-way handshaking method is adopted to discover the neighbors, which includes time synchronization by using devices such as GPS.

When it transmits only communication signals are sent, and the energy consumption is reduced compared to generating the integrated signal.

Mathematical analysis has been performed for the upper and lower bounds of the energy saving and discovery probability, and numerical results show that the proposal could save energy efficiently.

Simulation results show that the energy consumption of CRA [31] is much larger than that of RCI-SBA, while RCI-SBA consumes about half of the energy of the scan based algorithm (SBA) [32], thus the proposal can improve the energy efficiency of neighbor discovery.

A flexible neighbor discovery protocol is proposed in [3] for MANETs with social information recognition under a passive discovery framework, in which each mobile device is equipped with a wake-up radio, and accuracy is improved. Each node is also equipped with a radio transceiver that allows half-duplex, and the nodes can be active, passive (node waken up) or idle. When a mobile node, called sponsor node, launches a neighbor detection actively, it will broadcast a wake-up radio signal before the hello message. Within a certain distance, the node will be triggered from idle to active mode by its wake-up radio for a hello message sending. The passive neighbors, i.e., the idle mobile nodes, could be discovered with social recognition, and a mobile node is allowed to discover both active and inactive neighbors. The passive discovery framework over MANETs is introduced to use mobile social applications efficiently.

Through simulations in NS-2, the proposal shows higher efficiency in both discovery latency and energy consumption than the traditional deterministic protocols Disco [21], U-Connect [26] and SearchLight [22]. An implementation in a smartphone device is also available.

In the context of MSNs (Mobile Sensor Networks), a new neighbor discovery model is proposed in [4], in which the beacons are separated from the active slots and the broadcast of beacons can be dynamically adjusted to accelerate the discovery. Based on this model, a proactive wake up based neighbor discovery protocol which achieves energy-efficiency within a worst-case latency, called PWEND, is proposed. The proposal is applicable to both the slot-aligned and slot-unaligned scenarios, the parameters are theoretically optimized to maximize the performance, and the worst-case discovery latency can be minimized.

It is theoretically demonstrated that the PWEND can achieve the discovery with a strict discovery latency upper bound, and achieve the minimal worst-case discovery latency with a constant average energy consumption.

PWEND protocol is implemented and evaluated by state-based simulations through Matlab, regarding energy consumption and discovery latency, and the results show that the PWEND protocol outperforms other existing neighbor discovery protocols.

In a symmetric scenario, PWEND outperforms G-Nihao [24], Q-Connect$_A$ [34], Disco [21] and SearchLight (stripe) [22], regarding the discoveries versus latency metric when the duty cycle is 1%. The worst-case latency between the G-Nihao and PWEND are similar.

In asymmetric scenario, for duty cycles 1%, 5% and 10%, PWEND performs better than G-Nihao, SearchLight and Disco, regarding the discoveries versus latency metric.

In Table 2, a qualitative comparison of the recent related work discussed so far and the proposals are presented.

According to Table 2, most protocols can be used in mobile networks (MANETs), time is slotted, randomized schemes are used, they are asynchronous, they can be used in one-hop environments, and they all handle collisions. Furthermore, neither of them use full-duplex, pre-handshaking nor group testing. As for the proposals, they can only be used in static environments, time is slotted, they are randomized and asynchronous, suitable to be used in one-hop and multi-hop scenarios, they can cope with collisions. In CDH, the number of nodes in the network can be unknown.

Our randomized proposals differ from previous solutions since we aim at discovering all the neighbors with probability 1, even when the network is dense, i.e., composed of nodes that may have a large amount of neighbors. Therefore we overcome the problem of previous randomized protocols, which do not discover all the neighbors with probability 1. Our proposals achieve to reduce the latency and energy consumption, increase the throughput and the number of discovered neighbors versus packets sent ratio, and they are suitable for static multi-hop network environments.

3 Randomized proposals with collision detection

In this section, we present two proposals for static multi-hop wireless ad hoc networks, which we call CDPRR (Collision Detection Probabilistic Round Robin) protocol, and CDH (Collision Detection Hello) protocol, whose operation is based on collision detection.

3.1 System overview and assumptions

According to Fig. 1, the CDH protocol achieves the neighbor discovery by exchanging BROADCAST packets between the nodes in a slot (round) and the protocol is handshake-based. First, node i sends a BROADCAST packet containing its identifier towards the nodes within transmission range in a randomly chosen time ti. Then, node j also sends the BROADCAST containing its identifier in a randomly chosen time tj. At the end of the round (w), both nodes send a BROADCAST containing an array that indicates what messages collided.

As for the CDPRR protocol, shown in Fig. 2, the neighbor discovery is also accomplished by exchanging BROADCAST packets in a handshake-based manner. Node i sends a BROADCAST packet containing its identifier if a randomly

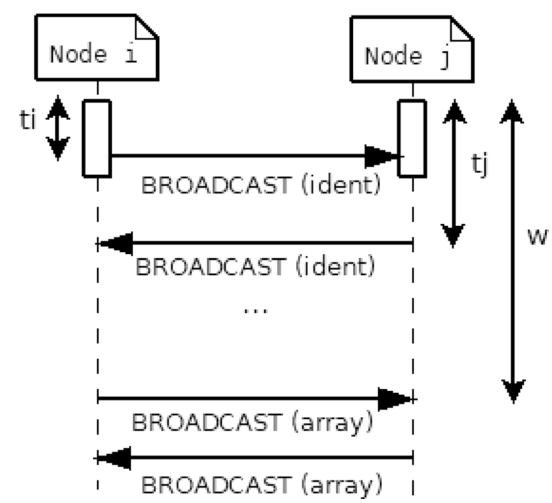

Fig. 1 CDH protocol

Table 2 Qualitative comparison of recent related work protocols and the proposals

	[12]	[13]	[14]	[15]	[16]	[17]	[3]	[4]	CDH	CDPRR
Mobile network	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No
Time slotted	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Randomized	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes
Asynchronous	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
One-hop	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Multi-hop	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes
N unknown	Yes	Yes	Yes	No	No	No	No	No	Yes	No
Handle collisions	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Full duplex	No	No	No	No	No	No	No	No	No	No
Pre-handshaking	No	No	No	No	No	No	No	No	No	No
Group testing	No	No	No	No	No	No	No	No	No	No

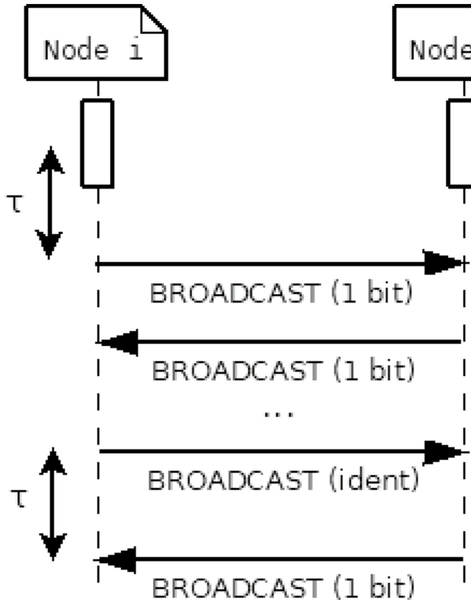

Fig. 2 CDPRR protocol

chosen state is transmitting, otherwise node i is listening. At the end of the round (of slot width τ), the nodes send back a bit to indicate whether the messages collided or not.

In Fig. 2, an example of operation of CDPRR is shown.

First, there is a round in which both nodes are listening, and at the end of the round both nodes send a bit towards other nodes.

Later on, node i is in transmitting state and node j is listening. At the end of the round, node j sends back a bit towards node i indicating whether the message collided or not.

In Sects. 3.2 and 3.3 we will explain more deeply the operation of these two proposals.

Regarding our two approaches we assume that the time is slotted in rounds and all the nodes know the slot width, each node is equipped with a limited range radio transceiver, all the nodes have the same transmission range, and they can be either transmitting or receiving but not simultaneously. Moreover, the nodes are randomly deployed in a given area, they cannot move in the deployment area, each node has a unique identifier, e.g., MAC address or manufacturer serial number, which distinguishes it from the other nodes, the nodes are asynchronous, although they require synchronization in slot boundaries. In addition, channel collisions may exist, the nodes can detect collision and termination conditions, both protocols are handshake-based, each node has an internal memory to save a neighbor table. Furthermore, the number of nodes is known by every node in the network in CDPRR, whereas it is unknown in CDH. As for the CDH protocol, the nodes can start transmission at different time instants.

3.2 CDH model

In this Section, we proceed to present CDH, our randomized neighbor discovery proposal, which are based on collision detection.

According to this protocol, the time is slotted in rounds, being the slot width ω, as shown in Fig. 3. Each node can be in one of three possible states: Transmit, Listen, and Success, the latter state meaning that the node managed to transmit successfully in previous rounds. These states and the transitions between them can be seen in Fig. 4.

According to Figs. 3 and 4, if a node is not in state Success in a round, the node independently and randomly chooses a time instant t_i, which might be different among nodes in the same round, and different among rounds of the same node, in such a way that $0 \leq t_i \leq \omega - \tau$. After listening (state Listen), the node transmits a single BROADCAST message per round beginning in t_i during a time τ, i.e., the node is in state Transmit, and then keeps listening for incoming messages in state Listen during the rest of the slot for a total listening time of size $\omega - \tau$. The BROADCAST message will contain the identifier of the source node.

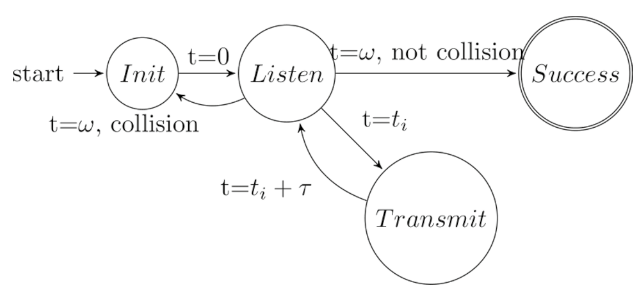

Fig. 4 CDH state machine

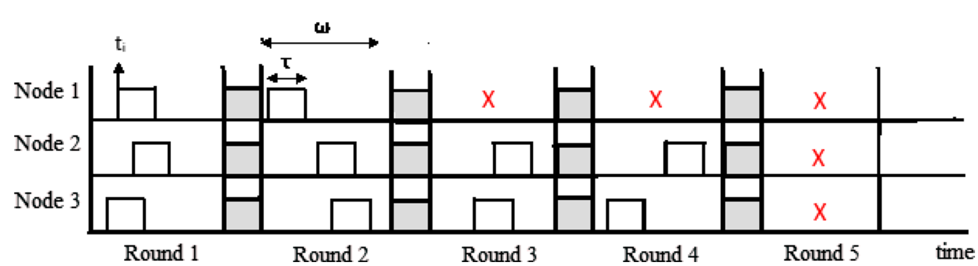

Fig. 3 CDH protocol example (timeline)

Otherwise, if a node is in state Success in a round, meaning that it transmitted successfully in previous rounds, which is shown by a red X mark in Fig. 3, it will not change the state in the following rounds as shown in Fig. 4, and it will remain listening for incoming BROADCAST messages from the other nodes.

At the end of the round, after having exchanged the BROADCAST messages, the nodes perform collision detection.

We say that a collision is detected if the received BROADCAST packets of two or more nodes overlap in time. Otherwise, we say that a node transmitted successfully.

If a node manages to transmit successfully, i.e., a collision did not occur, the rest of the nodes within transmission range save the identifier of this node in their neighbor tables.

After performing collision detection, the nodes send back a BROADCAST message containing an array of bits indicating the collision situation, shown in Fig. 3 as grey squares.

A ‘1’ value in the jth bit in this array means that the node with identifier j transmitted successfully, while a ‘0’ value indicates that its BROADCAST message collided.

As soon as the whole array is in the channel, all the nodes change to state Listen, and they sense the channel waiting for the array from the other nodes. When a BROADCAST message containing the array reaches a node, the node checks if the position in the array corresponding to its identifier takes the value ‘1’. In this case, this node changes its state to Success, and remains in this state until the algorithm ends as shown in Fig. 4. Furthermore, it will not contend from that moment on, and it will keep listening, as shown in Fig. 3.

According to Fig. 3, if a collision occurs between node i and node k, meaning that the kth position of the array is ‘0’, those nodes go on contending in the next round. When all the nodes have transmitted successfully, which means that all the nodes are in state Success, the algorithm ends.

So, this algorithm includes a termination detection mechanism in which each node checks if all the nodes within its transmission range have transmitted successfully. This is achieved by finding out whether there is no signal in the channel during a round, which means that none of the nodes within transmission range sent a BROADCAST. In this case, the algorithm ends.

As we observe from the example in Fig. 3, where each node is placed within transmission range of all the others in a one-hop scenario and the nodes are laid out in a MxM grid, in the first round the messages of all 3 nodes overlap in time. Thus, they all continue contending in the next round. In round 2, node 1 transmits successfully, and therefore it will not go on contending in the next rounds, as signaled by the red X mark in rounds 3, 4 and 5, while the messages of nodes 2 and 3 overlap in time, and so they continue contending in round 3. In round 3 there is again a collision between nodes 2 and 3. In round 4 both nodes 2 and 3 transmit successfully. At the end of round 4, all the nodes have already transmitted successfully, and the algorithm ends in round 5.

3.3 CDPRR model

In CDPRR, the time is also slotted in rounds, and each node can be in one of three possible states in a round: transmitting T, listening L or success S, as shown in Fig. 5, the state machine for CDPRR that summarizes the operation of the protocol.

According to Fig. 5, in each slot if a node is not in state S, meaning that it did not transmit successfully in previous rounds, it independently and randomly chooses either to transmit a BROADCAST message keeping in state T with probability $\frac{1}{N}$, or to listen, keeping in state L with probability $1-\frac{1}{N}$, being N the number of nodes in the network. The state chosen may be different among rounds of the same node, (e.g., a node might select a state T in a round and L in others), and can be different among nodes in the same round (e.g., a node might select a state T and another node L in the same round).

Otherwise, if the node is in state S, it will remain in this state until the algorithm ends, and it keeps listening.

According to Fig. 6, in state T the node sends a single BROADCAST (ident) message containing its identifier in a round being ident its identifier during τ, while in states L and S the node remains listening for incoming messages from the nodes within transmission range.

At the end of each round, if the node chose state T, it proceeds to sense the channel, while a collision detection mechanism is performed if the node chose state L, and two cases may take place:

- The nodes in state L detect a collision: they send back a bit ‘0’, which is received by the nodes that were in state T during the round. Then, a new round begins for the nodes in state T and L.
- The nodes in state L do not detect a collision: they send back a bit ‘1’, which is received by the node that was

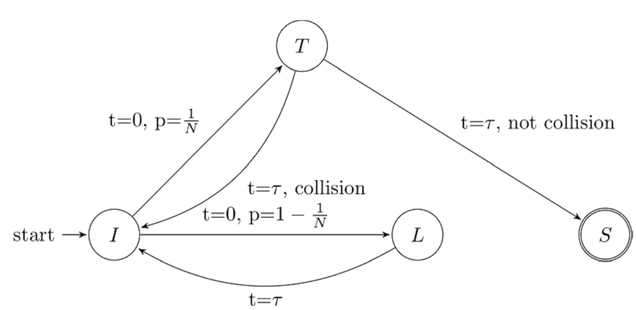

Fig. 5 CDPRR state machine

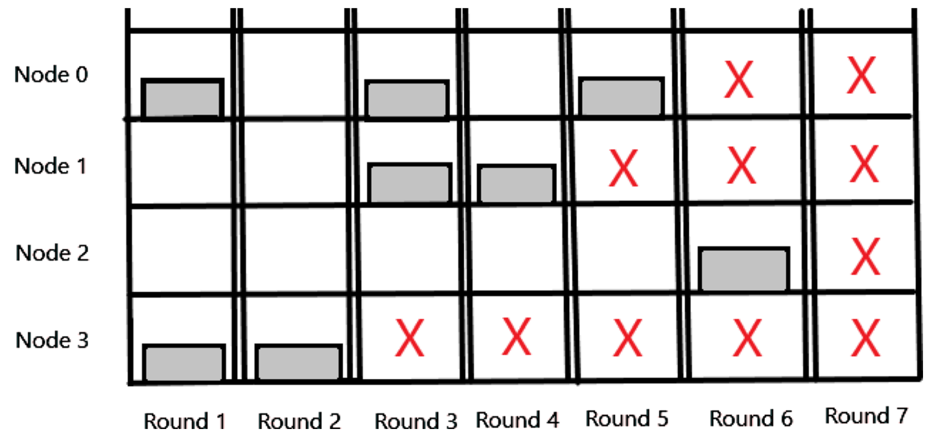

Fig. 6 CDPRR protocol example (timeline)

in state T during the round. Then, the node in state T changes the state to S and will remain in this state until the end of the algorithm (it keeps listening for incoming messages), and the nodes in state L update their neighbor tables with the identifier of the node in state T.

Then, a termination detection mechanism is performed. If all the nodes transmitted successfully, which means that they are all in state S, the algorithm ends; otherwise a new round begins.

In Fig. 6, we also provide an example of operation of CDPRR, which we proceed to comment. Each node is placed within transmission range of all the others in a one-hop scenario, and laid out in an MxM grid. In round 1, both nodes 0 and 3 are in state T, thus a collision occurs and all the nodes continue contending in the next round. In round 2, only node 3 transmits successfully, and so it will stop contending from then on, and a red X mark indicates this situation. In round 3, there is again a collision; in round 4, node 1 manages to transmit successfully, while nodes 0 and 2 continue contending in the next rounds; in round 5, node 0 transmits successfully. Finally, at the end of round 6, node 2 manages to transmit successfully, and in round 7 all the nodes transmitted successfully, meaning that the algorithm finishes.

4 Simulation and results

In this section we assess the performance of the proposed protocols in comparison with the protocols used as reference: HELLO and PRR. For our experiments we relied on the Castalia simulator version 3.2 [11].

4.1 Overview of reference protocols

As reference for our study, we have decided to choose two randomized algorithms from the literature: the PRR protocol [7], and the Hello Protocol [10]. We chose them as reference because they are classical protocols, and typically used for performance comparison purposes in previous related works. Furthermore, by presenting both proposals we also aimed at improving those reference protocols.

In the Hello protocol the time is slotted in rounds (slot width ω). In each round each node transmits a single packet in a randomly chosen time instant t_i during τ and listens during the remaining time $\omega-\tau$. This time t_i has been chosen so that $0 \leq t_i \leq \omega-\tau$ and it may be different among nodes in the same round and among rounds in the same node. A collision occurs when two or more nodes transmit at the same time, i.e., the packets overlap. Otherwise, a successful transmission takes place and a neighbor is discovered. The number of rounds must be carefully chosen since after a finite number of rounds the protocol ends. Furthermore, the protocol is not handshake-based.

As for the PRR protocol, the time is also slotted in rounds (slot width τ), and in each slot the nodes choose to transmit (state T) with probability $\frac{1}{N}$ or listen (state L) with probability $1-\frac{1}{N}$. The state chosen may be different among rounds of the same node, (e.g., a node might select a state T in a round and select L in others), and can be different among nodes in the same round (e.g., a node might select a state T and other nodes state L in the same round). When two or more nodes try to transmit at the same time, a collision occurs. Otherwise, a node transmitted successfully and thus a neighbor discovery takes place. Again, the number of rounds must be carefully set and the protocol is not handshake-based.

Table 3 presents a qualitative comparison of the neighbor discovery protocols used as reference, along with our two proposals. Among the most important characteristics shown in Table 3, notice that Hello and PRR are randomized, they are asynchronous although they require synchronization in slot boundaries, and both can be used in multi-hop networks, although none of them is able to discover all their neighbors with probability 1, and they are not handshake-based. On the other hand, our CDPRR and CDH proposals are designed to be used in both one-hop and multi-hop networks, they can

Table 3 Qualitative comparison of the proposals and reference protocols

	[10]	[7]	CDH	CDPRR
Static network	Yes	Yes	Yes	Yes
Mobile network	No	No	No	No
Randomized	Yes	Yes	Yes	Yes
Time slotted	Yes	Yes	Yes	Yes
N known	No	Yes	No	Yes
Requires synchronization	No	No	No	No
One-hop	Yes	Yes	Yes	Yes
Multi-hop	Yes	Yes	Yes	Yes
Collisions loose transmission	Yes	Yes	No	No
Packet loss detection	No	No	No	No
Collision detection	No	No	Yes	YES
Termination detection	No	No	Yes	Yes
Start transmission at different times	Yes	No	Yes	No
Discovers all neighbors	No	No	Yes	Yes
Handshake-based	No	No	Yes	Yes
Requires great number of slots	No	Yes	No	No
Requires N great for proper operation	No	Yes	No	No
Protected against packet loss	No	No	Yes	Yes

detect collisions and termination conditions, and they are able to discover all the neighbors with probability 1 even when the network is dense, meaning that it is composed of nodes with a huge amount of neighbors, and they are handshake-based. Furthermore, as rounds go by, there are less nodes contending, thus the discovery probability increases, the collision probability is reduced, and the discovery time is also reduced.

As for the CDH protocol, it allows nodes to start transmission at different time instants and follows more realistic assumptions, such as the nodes do not need to know the number of nodes in the network.

4.2 Simulation setup and methodology

To obtain the simulation results for the Hello, PRR, CDH and CDPRR protocols, we used the same simulation scenario. For this purpose, we varied the number of nodes in the network to test the performance regarding network scalability. For the PRR and Hello protocols, we set the number of rounds since, after a finite number of rounds both neighbor discovery algorithms end.

The simulation tool that we used for comparison purposes is Castalia version 3.2 [11], based on OMNET++ and it is basically used to simulate WSN (Wireless Sensor Networks) and BAN (Body Area Networks). In our case, it fully meets the requirements for validating neighbor discovery protocols in static multi-hop wireless ad hoc network environments.

For the Hello and CDH protocols we set a slot width of $\omega = N x \tau$, being N the number of nodes in the network and τ the time a node is transmitting. For all the protocols under test we have set an identical $\tau = 0.07$ s.

We defined (i) a deployment area of 10 m × 10 m for the one-hop setting, in which all the nodes are within transmission range of all the others, and also (ii) an area of 100 m × 100 m for the multi-hop scenario, in which only some nodes are within transmission range of the others, and N nodes are organized according to M × M grids.

To obtain the results and manage channel collisions, a collision model has been set using the collisionModel parameter of Castalia 3.2, which can take the values 0 (no collisions), 1 (simplistic model for collisions), or 2 (additive interference model).

We set the collision model to the additive interference model, i.e., collisionModel parameter set to 2, the most realistic collision model, for all the experiments, since the nodes must cope with channel collisions.

The main goal of all the neighbor discovery protocols is to discover all the neighbors, or nearly all of them, in a reduced amount of time. Therefore, for the simulations carried out, we chose the Neighbor Discovery Time and the Number of Discovered Neighbors as main output metrics. Therefore, a protocol will be better than others if its Neighbor Discovery Time is lower and the Number of Discovered Neighbors is higher. Furthermore, we obtained the Energy consumption, since the nodes are equipped with batteries that may deplete in a given time, the Throughput and the Number of discovered neighbors versus packets sent ratio, for the 4 protocols under test.

The radio model we used to evaluate the performance is ZigBee (CC2420).

In addition, we set the transmission power to − 5 dBm, the packet rate to 5 packet/s, and the packet size to 2500 bytes.

The simulation parameters are summarized in Table 4.

For performance comparison purposes we set a specific number of rounds for PRR (i.e., 10 N rounds in one-hop and 6 N in multi-hop) and Hello (i.e., 0.5 N in one-hop and 0.25 N in multi-hop).

Since the Neighbor Discovery Time is inversely related to the Number of Discovered Neighbors, we aim at choosing a number of rounds so that the proposals improve the reference protocols regarding both metrics or worsen the reference protocols regarding both metrics, if possible. After several simulations we found that by setting the number of rounds above, the proposals outperform the reference protocols regarding both metrics.

Table 4 Simulation parameters

Parameter	Value
Static	True
Radio model	CC2420
collisionModel	2
Transmission power	−5 dBm
Packet rate	5 packet/s
Packet size	2500 bytes
Slot width Hello and CDH	ω = N × τ
τ	0.07 s
Size one-hop	10 m × 10 m
Size multi-hop	100 m × 100 m
Deployment	Grid M × M
Number of rounds PRR one-hop	10 × N
Number of rounds Hello one-hop	0.5 × N
Number of rounds PRR multi-hop	6 × N
Number of rounds Hello multi-hop	0.25 × N

4.3 Performance results

Next, we will focus on the simulation results we obtained to compare the performance of all the target protocols under both one-hop and multi-hop settings.

4.3.1 Neighbor discovery time

First, we proceed to present the results for the one-hop scenario, which is a simpler case, although applicable to many real situations, especially when the radio technology used has a very high communications range.

When we talk about neighbor discovery time, we refer to the amount of time that an algorithm takes to finish.

According to Fig. 7, the CDPRR protocol outperforms the other solutions regarding the neighbor discovery time, and it follows a moderate increasing trend as the number of nodes in the network gets bigger. CDH also shows good results, followed by PRR with 10 N rounds, and finally Hello with 0.5 N rounds has the worst performance.

It is obvious that, as the number of nodes grows, the neighbor discovery time increases for CDH and CDPRR since more nodes have to manage to transmit successfully. As rounds go by, in CDH and CDPRR, there are less nodes contending, and this is the reason why the discovery time for these two protocols is reduced in comparison to that for Hello and PRR.

To obtain Fig. 7, the additive interference model, i.e., the most realistic collision model, has been used, setting the parameter collisionModel parameter of Castalia 3.2 to 2, although identical results are obtained for the other two collision models.

Next, we present the results obtained through simulation in a more realistic scenario: a multi-hop network, in which some nodes are within transmission range of others.

First, we will show the results obtained regarding neighbor discovery time when the collisionModel parameter is set to 2, i.e., the most realistic collision model, although identical results are obtained for the collision-less case, and for the simplistic model for collisions. The neighbor discovery time increases when the number of nodes grows since there are more nodes that have to manage to transmit successfully in CDH and CDPRR.

According to Fig. 8, CDPRR outperforms the other solutions, followed by CDH, that is better than PRR with 6 N rounds, and finally Hello with 0.25 N rounds presents the worst overall behavior.

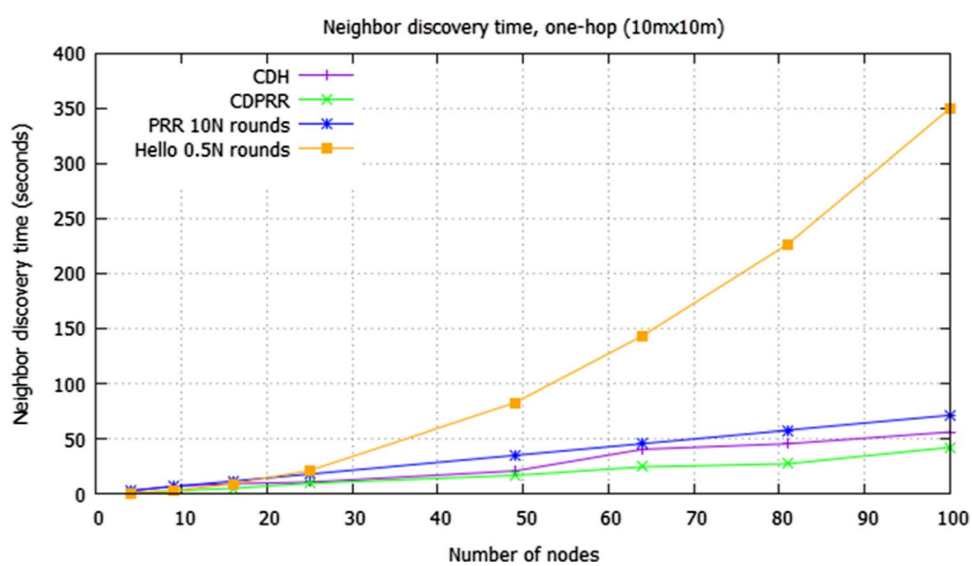

Fig. 7 Neighbor discovery time comparison: one-hop setting, PRR with 10 N rounds, Hello with 0.5 N rounds, collisionModel 2, transmission power −5 dBm

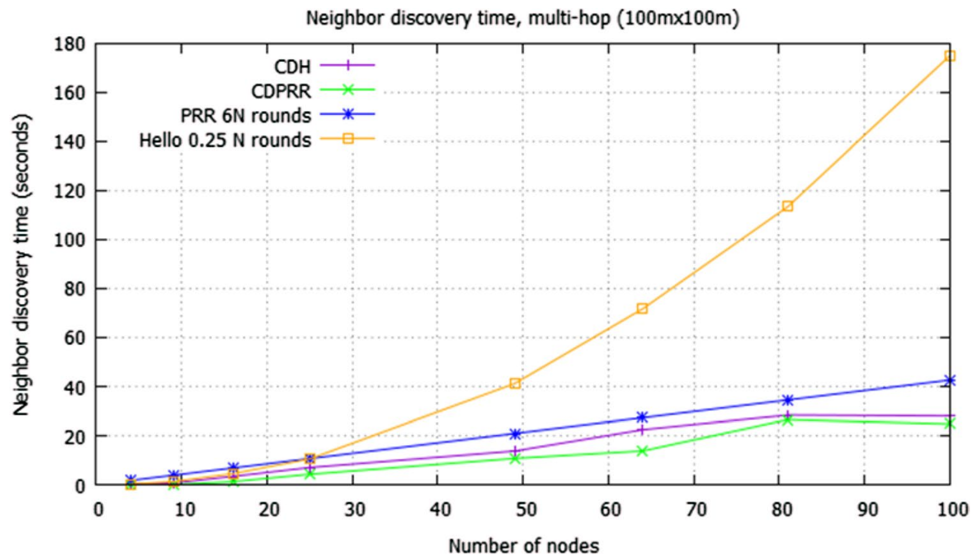

Fig. 8 Neighbor discovery time comparison: multi-hop scenario, PRR with 6 N rounds, Hello with 0.25 N rounds, collisionModel 2, transmission power −5 dBm

4.3.2 Number of discovered neighbors

First, we present the results regarding the number of discovered neighbors in a one-hop setting.

We set the number of rounds for PRR to 10 N and for Hello to 0.5 N.

For the collision-less case, in which the collisionModel parameter of Castalia 3.2 was set to 0, we found that all the protocols present the same ideal behavior, meaning that all the nodes manage to discover their N-1 neighbors in the one-hop network as there are no collisions.

Regarding the results obtained using the most realistic collision model, i.e., setting the collisionModel parameter to 2, which are shown in Fig. 9, CDH and CDPRR present optimal results discovering all the N-1 neighbors, which means that they achieve the ideal behavior and outperform the other solutions. Next, PRR with 10 N rounds and Hello with 0.5 N rounds present similar results, although Hello with 0.5 N rounds has the worst results for low number of nodes. Notice that Hello has the worst performance because the protocol discovers "nearly" all of the neighbors when the number of nodes is low, as stated in [10].

We have considered interesting to test the protocols under different collision models such as "no collisions", "simplistic model for collisions" and "additive interference model", which were first suggested in [10].

Through simulation, we found that the results regarding the number of discovered neighbors is similar for both collision Model 1 and 2.

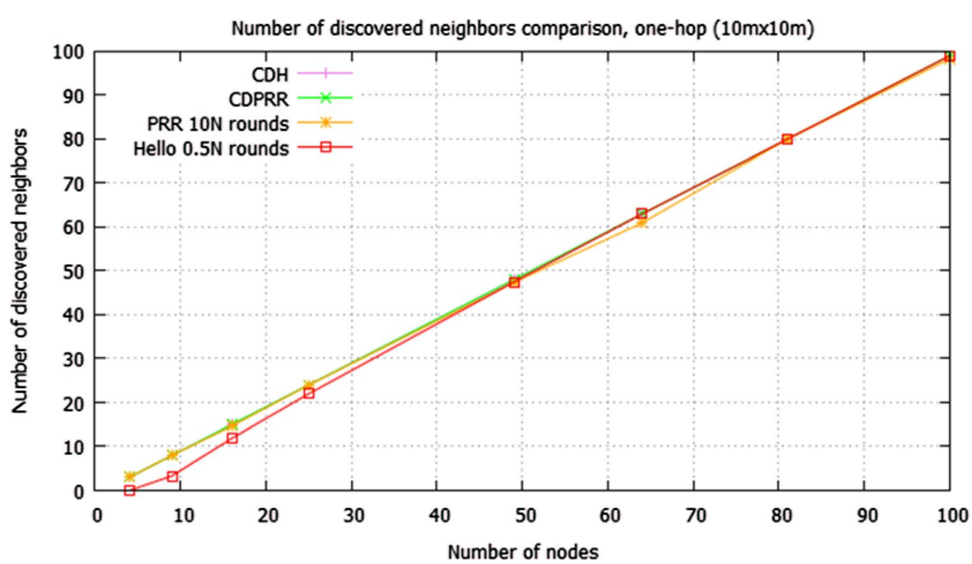

Fig. 9 Average number of discovered neighbors comparison: one-hop scenario, PRR with 10 N rounds, Hello with 0.5 N rounds, collisionModel 2, transmission power −5 dBm

Next, the results obtained for the number of discovered neighbors metric in a multi-hop scenario, setting different collision models, are presented.

For the collision-less case, all the protocols achieve optimal results, meaning that all the protocols manage to discover all their neighbors, since there are no collisions.

According to Fig. 10, that shows the results when the collisionModel parameter is set to 2, that is, the most realistic collision model, CDH and CDPRR manage to discover all their neighbors and outperform the other solutions. Hello with 0.25 N rounds presents a slightly worse performance than CDH and CDPRR, and finally PRR with 6 N rounds offers the worst results. The performance for PRR is the worst for large networks, as stated in [11]. For a number of nodes less than 10, none of the nodes discover any neighbor, as all the nodes are out of the transmission range of all the others.

Again, in this section, we have considered interesting to test the protocols under different collision models, such as "no collisions", "simplistic model for collisions" and "additive interference model", which were first suggested in [10].

We found that the results regarding the number of discovered neighbors are similar for both collisionModel 1 and 2.

4.3.3 Energy consumption

First, the simulation results for a one-hop setting are shown.

According to Fig. 11, all the solutions present an increasing trend with the number of nodes regarding energy consumption. CDPRR outperforms the other solutions, while CDH performs better than PRR with 10 N rounds, and Hello with 0.5 N rounds presents the worst performance. This increasing trend is mostly due to the growth in Neighbor

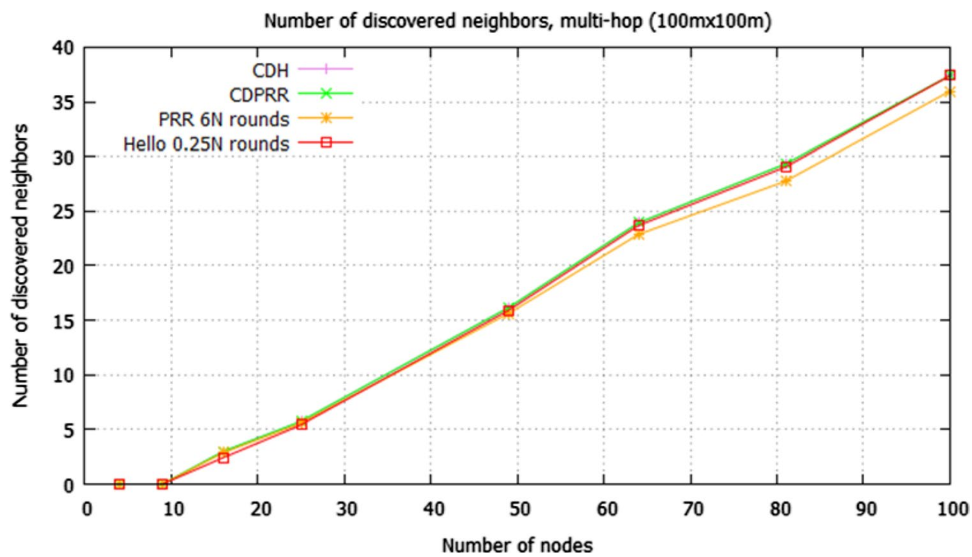

Fig. 10 Average number of discovered neighbors comparison: multi-hop scenario, PRR with 6 N rounds, Hello with 0.25 N rounds, collisionModel 2, transmission power −5 dBm

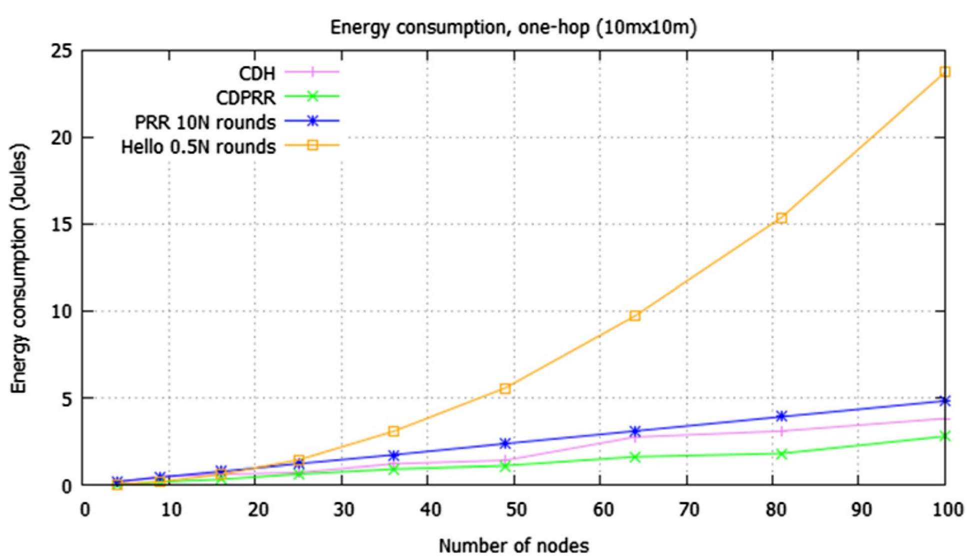

Fig. 11 Average Energy consumption comparison: one-hop scenario, PRR with 10 N rounds, Hello with 0.5 N rounds, collisionModel 2, transmission power −5 dBm, packet rate 5 packet/s, packet size 2500 bytes

discovery time and, as a remarkable result, both Figs. 7 and 11 show a similar trend.

Then, the results for a multi-hop setting are presented.

Again, as shown in Fig. 12, all 4 protocols follow an increasing trend with the number of nodes regarding energy consumption. CDPRR presents better performance than the other protocols, while CDH outperforms PRR with 6 N rounds, and Hello 0.25 N presents the worst performance. Notice that Figs. 8 and 12 follow the same trend since, as the time increases, the energy consumption also grows.

4.3.4 Throughput

First, we present the results obtained in a one-hop setting.

As shown in Fig. 13, CDPRR outperforms the other solutions regarding throughput, while its performance is similar to CDH when the number of nodes is above 50. CDH presents better performance than Hello with 0.5 N rounds, and PRR with 10 N rounds presents the worst performance, although Hello with 0.5 N rounds and PRR with 10 N rounds present similar performance when the number of nodes is above 30. The decreasing trend for all the protocols under test is due to the growth in collisions since, as the number of nodes increase, fewer packets are received per second. It is obvious that in CDH and CDPRR the throughput is higher than that of Hello and PRR because, as rounds go by, there are less collisions in CDH and CDPRR, thus more packets are received.

Next, we show the results obtained for the multi-hop case.

According to Fig. 14, when the number of nodes is above 15 CDH outperforms the other solutions regarding throughput. Moreover, above 35 nodes, CDPRR is better than Hello with 0.25 N rounds, and PRR with 6 N rounds presents the worst performance. Moreover, the networks of size less than

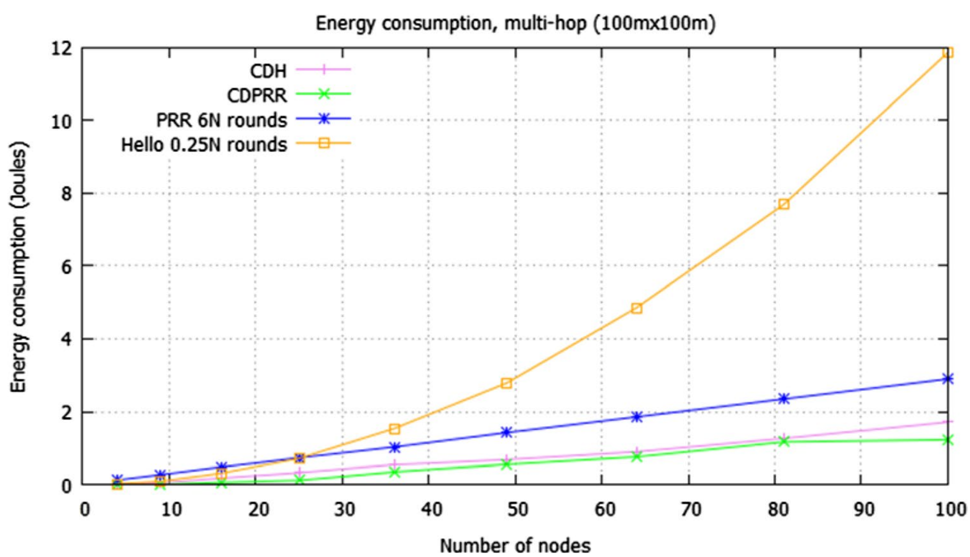

Fig. 12 Average Energy consumption comparison: multi-hop scenario, PRR with 6 N rounds, Hello with 0.25 N rounds, collisionModel 2, transmission power −5 dBm, packet rate 5 packet/s, packet size 2500 bytes

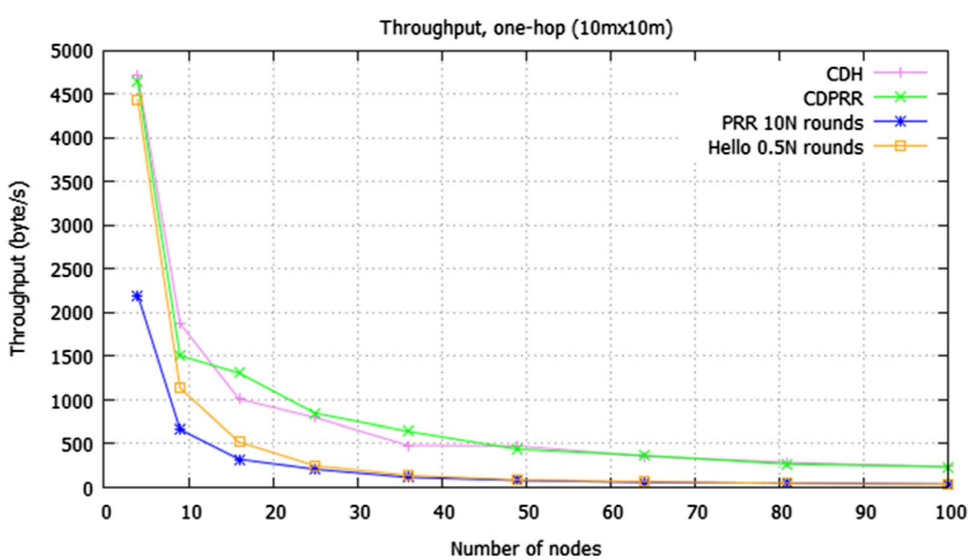

Fig. 13 Average Throughput comparison: one-hop scenario, PRR with 10 N rounds, Hello with 0.5 N rounds, collisionModel 2, transmission power −5 dBm, packet rate 5 packet/s, packet size 2500 bytes

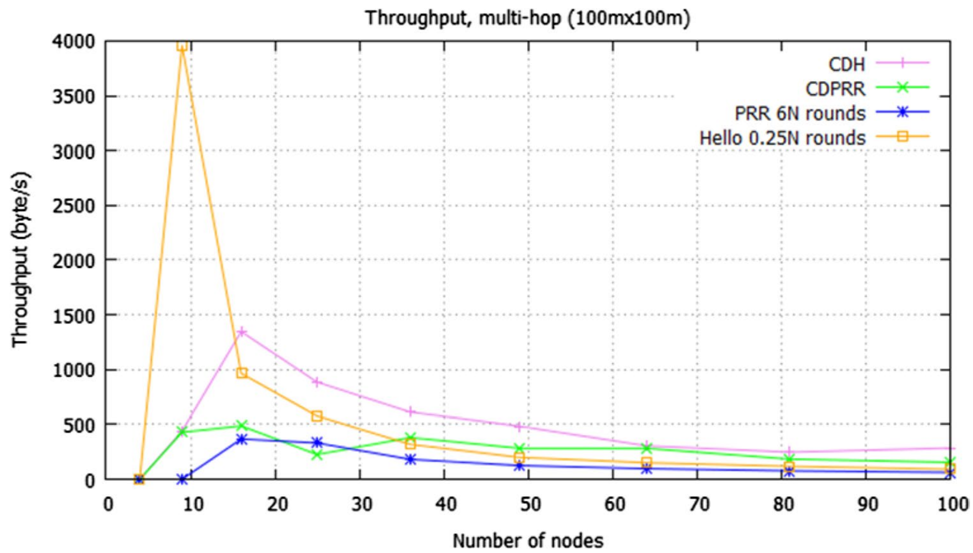

Fig. 14 Average Throughput comparison: multi-hop scenario, PRR with 6 N rounds, Hello with 0.25 N rounds, collisionModel 2, transmission power −5 dBm, packet rate 5 packet/s, packet size 2500 bytes

9 nodes present a throughput of 0 byte/s since all the nodes are out of the transmission range of all the others.

The decreasing trend is mostly due to the growth of collisions, causing that less packets arrive per second. Again, we conclude that in CDH and CDPRR the throughput is higher than that of Hello and PRR because, as rounds go by, there are less collisions thus more packets are received.

4.3.5 Discovered neighbors versus packets sent ratio

First, we proceed to present the results for the one-hop case.

According to Fig. 15, CDPRR outperforms the other solutions, CDH shows better results than PRR with 10 N rounds and Hello with 0.5 N rounds presents the worst performance.

Mainly, as the time consumption is reduced, there are less packets sent for the same number of discovered neighbors and thus the number of discovered neighbors versus packets sent ratio is higher. As CDPRR and CDH present a lower time consumption, it is obvious that the number of discovered neighbors versus packets sent ratio is higher than that of the reference protocols.

Then, we proceed to present the results for the multi-hop case.

As shown in Fig. 16, CDPRR also outperforms the other solutions, while CDH presents better results than PRR with 6 N rounds and Hello with 0.25 N rounds shows the worst results.

The results for a number of nodes below 10 are 0 since all the nodes are out of the transmission range of all the others.

Again, as the time consumption is lower, less packets are sent for the same number of discovered neighbors and therefore the number of discovered neighbors versus packets sent

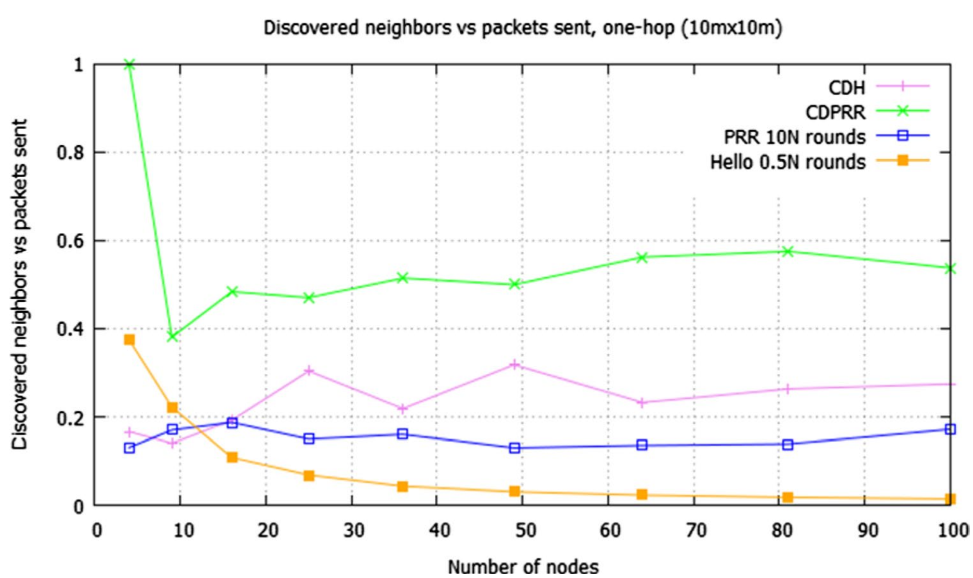

Fig. 15 Number of discovered neighbors versus packets sent ratio comparison: one-hop scenario, PRR with 10 N rounds, Hello with 0.5 N rounds, collisionModel 2, transmission power −5 dBm

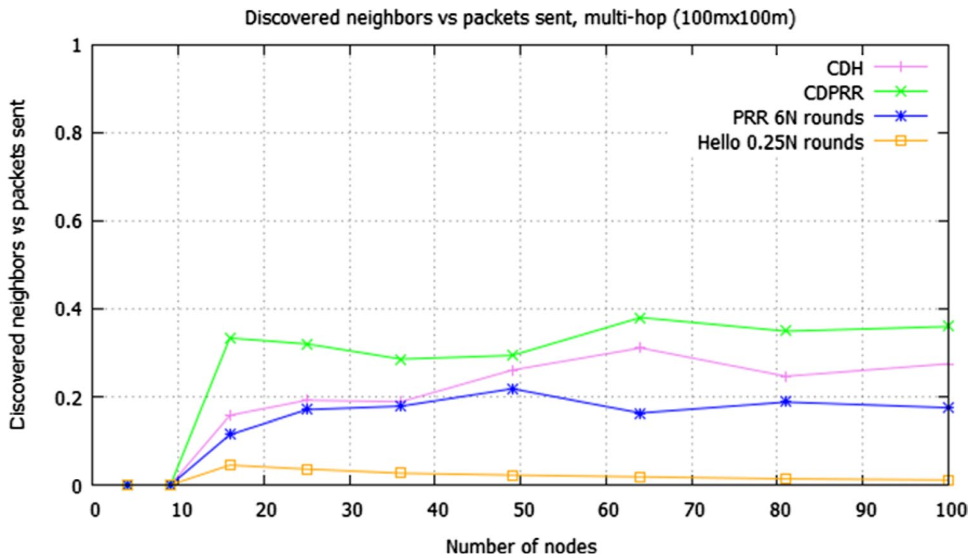

Fig. 16 Number of discovered neighbors versus packets sent comparison: multi-hop scenario, PRR with 6 N rounds, Hello with 0.25 N rounds, collision-Model 2, transmission power −5 dBm

ratio is higher. As CDPRR and CDH present a lower time consumption, it is obvious that the number of discovered neighbors versus packets sent ratio is higher than that of the reference protocols.

5 Conclusion

In this work, we have carried out a study of neighbor discovery strategies for static multi-hop wireless ad hoc networks taking into account the presence of collisions.

In this context, two protocols have been chosen from the literature to be used as reference and implemented in Castalia 3.2 simulator for comparison purposes: PRR and Hello. Moreover, we have proposed two randomized protocols for static multi-hop wireless ad hoc networks, which take the advantages of collision detection, called CDH (Collision Detection Hello) and CDPRR (Collision Detection Probabilistic Round Robin), and they have also been implemented in the same simulator in order to be evaluated and compared against the reference protocols.

The experiments have been focused on both one-hop and multi-hop neighborhoods, and we chose the neighbor discovery time, the number of discovered neighbors, the energy consumption, the throughput, and the number of discovered neighbors versus packets sent ratio, as performance metrics.

According to the simulation results obtained in both settings, CDPRR presents better results in terms of time, energy consumption, and number of discovered neighbors versus packets sent ratio than CDH, Hello, and PRR, whereas, regarding the number of discovered neighbors, CDH and CDPRR outperform the reference protocols. As for the throughput, CDPRR outperforms the other solutions in a one-hop setting, while CDH is better than the other protocols in a multi-hop scenario.

Overall, we found that both proposals outperform the reference protocols regarding all five metrics in one-hop and multi-hop scenarios, they operate under more realistic assumptions, providing clear advantages such as being able to detect collisions and termination conditions, allowing all the nodes to discover all their neighbors with probability 1. Furthermore, CDH allows the nodes to start transmissions at any time instant, and the number of nodes can be unknown.

Moreover, the overall computational complexity, i.e., time consumption, for CDH and CDPRR, in both one-hop and multi-hop settings, is linear O(N), being N the number of nodes in the network.

The main limitations of the CDPRR protocol are that it needs to know the number of nodes in the network and the transmissions cannot be started at different time instants. However, CDH solves those limitations, allowing to ignore the number of nodes and start transmission at different time instants. Both CDH and CDPRR require synchronization in slot boundaries, they can only be used in static environments (i.e., they cannot be used in MANETs), the time must be slotted and no packet loss detection is available. Future ways to overcome these limitations are to develop or use an existing synchronization mechanism to be used before the neighbor discovery begins, and adapt the protocols to allow new neighbor joining and leaving in MANETs.

Among the practical applications, the proposals can be used in static wireless ad hoc scenarios in a multi-hop fashion or in spontaneous networks, such as a group of students that meet in a certain location to exchange information.

As possible future research works, we plan to propose and evaluate low energy consumption neighbor discovery protocols for static and mobile networks, as well as to achieve secure neighbor discovery protocols. Moreover, we will research the behavior in indoor environments [35, 36].

Acknowledgements This work has been partially supported by the "Ministerio de Economía y Competitividad" in the "Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia, Subprograma Estatal de Generación de Conocimiento" within the project under Grant TIN2017-84802-C2-1-P. This work has also been partially supported by European Union through the ERANETMED (Euromediterranean Cooperation through ERANET joint activities and beyond) project ERANETMED3-227 SMARTWATIR.

Compliance with ethical standards

Conflicts of interest Authors declare that they do not have conflict of interest.

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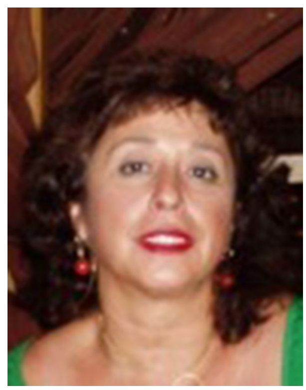

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