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Collision Avoidance Based Neighbor Discovery in Ad Hoc Wireless Networks

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Abstract

Neighbor discovery is an important first step after the deployment of ad hoc wireless networks since they are a type of network that do not provide a communications infrastructure right after their deployment, the devices have radio transceivers which provide a limited transmission range, and there is a lack of knowledge of the potential neighbors. In this work two proposals to overcome the neighbor discovery in static one-hop environments in the presence of collisions, are presented. We performed simulations through Castalia 3.2, to compare the performance of the proposals against that for two protocols from the literature, i.e. PRR and Hello, and evaluate them according to six metrics. According to simulation results, the Leader-based proposal ($O(N)$) outperforms the other protocols in terms of neighbor discovery time, throughput, discoveries vs packets sent ratio, and packets received vs sent ratio, and the TDMA-based proposal is the slowest ($O(N^2)$) and presents the worst results regarding energy consumption, and discoveries vs packets sent ratio. However, both proposals follow a predetermined transmission schedule that allows them to discover all the neighbors with probability 1, and use a feedback mechanism. We also performed an analytical study for both proposals according to several metrics. Moreover, the Leader-based solution can only properly operate in one-hop environments, whereas the TDMA-based proposal is appropriate for its use in multi-hop environments.

Keywords Ad hoc wireless networks · Neighbor discovery · Deterministic · Randomized · One-hop · Collisions

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1 Introduction

Ad hoc wireless networks are special type of network which do not provide a communications infrastructure after their deployment, and they are also conformed by devices which include radio transceivers providing a very limited transmission range. In such networks, some nodes have the ability of sending messages directly to their one-hop neighbors, while other nodes need several hops for the messages to reach its destination in a multi-hop manner, therefore each node must act as a router [1, 2].

Right after their deployment, the nodes must be able to self-configure in order to set a communications infrastructure. Due to the lack of infrastructure that can inform about the neighbors, as a first step after the deployment, each node must discover the neighbors, thus neighbor discovery protocols must be provided [3, 4].

In static environments, the nodes can not move in the deployment area. An example is a WSN, whose nodes are placed in a field to find the amount of water necessary [5]). On the other hand, in mobile networks (MANETs), the nodes can get in and out of the network or go in and out of other node's transmission range. A possible example could be a vehicular ad hoc network used to monitor weather conditions [6]).

In the randomized solutions developed for neighbor discovery algorithms the nodes transmit in a time which is randomly chosen or state and manages to discover all the neighbors with high probability (different from 1). As for the deterministic solutions, the nodes must transmit following a schedule and manage to discover all the neighbors with probability 1.

Among the applications of such networks [7] we can found the industrial (e.g., robot networks), medical (e.g., monitor patient), military (e.g., hostile environments), and teaching.

This work addresses neighbor discovery in static one-hop ad hoc environments and propose two solutions that take into account the existence of collisions.

Among the problems found in [8] and [5], we highlight the following: termination condition is not provided unless a number of rounds is set, and the neighbors are not discovered with probability 1, while in the protocol in [5] the number of nodes must be known. Therefore, the main goal is to propose protocols which know when to terminate the discovery process and enhance the probability of discovering all the neighbors.

There are several problems we must cope with while developing the protocols, such as the nodes must operate in static one-hop settings, only half-duplex operation is available, a random deployment of the nodes takes place in an area, collisions may take place, the protocol must discover all the neighbors with probability 1 and termination conditions must be provided.

This paper is an extended version of the paper sent to GCWOT'20 [9].

The main contributions of this work are: (i) Leader-based, a deterministic proposal that achieves to discover all the neighbors with probability 1, follows a predetermined transmission schedule, it includes a special node known as leader which starts the discovery, terminates the discovery according to the schedule, can only be used in one-hop environments, although it must know the total number of nodes in the network (ii) TDMA-based, a deterministic proposal that also achieves to discover all the neighbors with probability 1, follows a predetermined transmission schedule, terminates the discovery according to the schedule, can be used in both one-hop and multi-hop environments, although it must know how many nodes are there in the network, (iii) a qualitative comparison of the deterministic protocols found in the literature, (iv) a qualitative comparison of Hello, PRR and our proposals, (v) an analytical study of the proposals in terms of time and energy consumption, throughput, number of discoveries vs packets sent ratio, and packets received vs packets sent ratio, (vi) an implementation of the Leader-based, TDMA-based and the reference protocols has been performed in Castalia 3.2 simulator [10] in order to compare the performance of those protocols regarding the number of discovered neighbors and the above five metrics used in the analytical study.

The outline of this paper is as follows: Sect. 2 includes a description of related works and a qualitative comparison of both reference protocols and our proposals, Sect. 3 describes our proposals, the assumptions, models, analytical results, a description of the reference protocols, and the simulation scenario, Sect. 4 provides and discusses the simulation results, and in Sect. 5 some concluding remarks are made and future research directions are outlined.

2 Related Work

Next, we present and discuss a few deterministic protocols found in the literature. They mainly focus on enhancing the energy efficiency.

First, Disco [11] achieves the discovery in a reliable and asynchronous manner, it is tailored for mobile sensing applications and can operate at low duty cycles. According to its operation, the nodes must choose two prime numbers such that the sum of their reciprocals equals the duty cycle, and if after incrementing a counter, this quantity is divisible by at least one of the prime numbers, then it switches its radio on for an amount of time and finally either transmits or listens. A neighbor discovery takes place as soon as a pair of nodes turn their radios on in a given amount of time. Simulation results show that Disco outperforms Quorum [12] and Birthday protocols [5] regarding the time consumption for asymmetric scenarios. However, in symmetric scenarios, Disco behaves as well as Quorum.

SearchLight [13] is an asynchronous discovery protocol, which combines both deterministic and probabilistic components, and it is evaluated through a metric that includes energy consumption and discovery time. Authors conclude that, in the symmetric case, the protocol behaves as well as the probabilistic protocols in the average case. Furthermore, the protocol outperforms the deterministic protocols regarding the worst-case bounds, being its performance similar to that for the deterministic protocols in the asymmetric case. According to simulation results, SearchLight outperforms the existing solutions in terms of energy consumption and average discovery time for low duty cycles, while its performance is similar to other protocols in other cases. In [13], SearchLight-S (sequential) and SearchLight-R (randomized) are presented in order to determine the schedule, and conclude that a great advantage is achieved by the randomized proposal.

U-Connect [14] is a discovery protocol that manages to solve both symmetric and asymmetric cases. According to the operation, time is slotted, it does not require synchronization, and the nodes must choose different prime numbers (different duty cycles), thus the nodes wake-up in multiples of primes. Authors use a metric which consists in multiplying the energy and the latency to evaluate the proposal. U-Connect outperforms existing protocols for WSN (wireless sensor networks) regarding the latency, by setting a fixed duty cycle. For an asymmetric scenario, U-Connect behaves similarly than Disco [11], while in a symmetric scenario, U-Connect outperforms Quorum [12] and Disco regarding the energy consumption. Moreover, U-Connect is a unified protocol that solves the neighbor discovery problem in both symmetric and asymmetric scenarios.

Centron [15] is made up of two stages, i.e., core formation and neighbor discovery, and aims at minimizing collisions in crowded regions. In the first stage, messages are exchanged to establish a core group composed of a low number of nodes, that behaves as a "big mobile node" that is in charge of generating its duty cycle. In the second stage, the members composing the core launch the discovery, and the neighbor tables will be shared. Mathematical results have been obtained using Matlab, concluding that Centron outperforms existing solutions in terms of energy consumption. According to simulation results obtained using NS-3, show that Centron outperforms existing protocols regarding the average discovery latency, in a one-hop scenario. In addition, Centron manages to improve the discovery efficiency.

In [16] Hedis and Todis, two asynchronous neighbor discovery protocols, are presented. Hedis is a periodic protocol that uses slotted time, while Todis uses a trade-off between latency and duty cycle and deals with a larger amount of numbers than Disco [11] and U-Connect [14]. According to simulations, Hedis and Todis outperform existing solutions, and optimize the duty cycle, allowing to achieve lower energy consumption. However, Hedis and Todis, behave similarly in terms of latency. For both proposals, U-Connect, Disco and SearchLight [13], an implementation in Xiaomi Mi-Note smartphones (Android) is available. According to the real-world experiments, the results regarding latency varying the duty cycles agree with the simulation results. Authors conclude that Hedis represents the most appropriate protocol for its use in WSNs.

A Quorum-based [12] deterministic neighbor discovery protocol tailored for MANETs, is presented. According to its operation, it does not require synchronization, each node can be either transmitting, making use of a random back-off time before transmitting, or receiving. As usual, a successful discovery takes place when two neighbors switch tune their radios on the same frequency channel for a given amount of time. [12] provides a trade-off between time consumption and energy consumption, achieving a faster and low energy discovery. According to simulations, authors found that, both techniques proposed have similar results. On the other hand, the proposal requires a dedicated circuitry.

An interesting work can be found in [17], which shows a mechanism to choose neighbors for a particular type of wireless networks, i.e., group-based WSNs.

Table 1 summarizes the main characteristics of the deterministic protocols addressed in this Section.

According to the contents in Table 1, all the protocols discussed are deterministic, they do not require synchronization, the duty cycles handled are low, almost all may be used in both symmetric and asymmetric environments, and most of the protocols have been implemented.

Next, two related works which propose randomized protocols, are presented.

A protocol that manages to save energy during the deployment in static environments and performs the discovery in an efficient manner, is proposed in [5]. The authors present the Birthday protocols, i.e., a family of probabilistic protocols. A protocol that belongs to that family is the probabilistic PRR, a protocol which achieves to maximize the discovery probability. However, in networks composed by a huge amount of neighbors, the protocol could not discover some of the neighbors. Two similar protocols, which authors called Basic Hello protocol and an extended version Energy-aware Hello protocol are proposed in [8], where authors focus on the impact of collisions in the discovery tailored for static multi-hop networks. The Energy-aware Hello protocol aims at improving the energy

Table 1 Qualitative comparison of neighbor discovery protocols

	[11]	[13]	[14]	[12]	[16]	[15]
Asynchronous operation	✓	✓	✓	✓	✓	✓
Allows low duty cycles	✓	✓	✓	✓	✓	✓
Parameters used	$(p_{i1}, p_{i2}), (p_{j1}, p_{j2})$	$t \in Z$ (a prime)	p (a prime)	$m \in Z^+$	$n \in Z^+$ same parity / n, m odd	
Duty cycle value	$\frac{1}{p_1} + \frac{1}{p_2}$	$\frac{2}{t^i}$	$\frac{3 \times p+1}{2 \times p^2}$	$\frac{2 \times m-1}{m^2}$	$\frac{2}{n}$ / $\frac{3}{n}$	
Schedule period	$T = p_1 \times p_2$	$\frac{t^2}{2}$	$T = p^2$	$T = m^2$ AI (Advertise interval)	$n \times (n-1) / (n-2) \times n \times (n+2)$	
Asymmetric environment	✓	✓	✓		✓	✓
Symmetric environment	✓	✓	✓	✓	✓	✓
Switch radio on	Multiples of primes	Anchor slot(0) and probe	1 of each p slots	Frequency channel in an AI	Anchor and probing / multiples of $n-2$ or n or $n+2$	
Balan/not balan primes	✓					
Implementation available	Telos motes (Tiny OS)	Smartphones Android G1	FireFly Badge		Mi-Note Android (BLE)	
May be used in MANETs	✓	✓	✓	✓	✓	✓

efficiency. In [8], authors deal with the collisions in different manners, by introducing three radio models.

Both the PRR and the Basic Hello protocol have been chosen to be used as reference to compare with our proposals in Sect. 4. Moreover, a more detailed description about them is available in Table 2.

Next, several more recent neighbor discovery protocols are presented.

KPND [18], tailored for mobile environments, achieves the discovery quickly and efficiently. It makes use of the Kalman filter theory, hello messaging, and GPS, and considers both temporal and spatial node movements and trajectory information, and it handles the nodes joining and leaving. Simulations results obtained with NS3.28 and Mobisim, allow authors to conclude that KPND outperforms HP-AODV, ARH [19] and ROMSG [20], regarding the hello overhead, the number of hello messages, the accuracy rate, and the error rate.

A radar assisted protocol is described in [21] for MTC (Machine-type communication), and achieves low time consumption. Several algorithms are presented in [21]. According to numerical results, it is allowed to conclude that the time consumption of the proposal is improved by using the prior information obtained from the radar. According to simulations, the speed can be increased by setting appropriate parameters. Furthermore, the speed increases much more slowly without prior information provided by the radar. In addition, the proposal manages to outperform the CRA [22] in terms of time consumption. A practical drawback is that radar and communications must be integrated, synchronization is assumed, and only half-duplex mode is available.

[23] presents a protocol that provides distributed network control suitable for highly dynamic resource constrained MANETs and an integration of routing, scheduling and network/neighbor discovery. The protocol performs route and neighbor discovery at the same

Table 2 Qualitative comparison of related work protocols and our proposals

	[8]	[5]	Leader	TDMA
Use in static environment	✓	✓	✓	✓
Use in mobile environment				
Randomized protocol	✓	✓		
Time slotted	✓	✓		
N unknown	✓			
Requires synchronization in slot boundaries	✓	✓	✓	✓
Half-duplex	✓	✓	✓	✓
One-hop setting	✓	✓	✓	✓
Multi-hop setting	✓	✓		✓
Sleep mode available				
Collisions considered	✓	✓	✓	✓
Collisions do not produce transmission loss			✓	✓
Packet loss detection				
Leader required			✓	
Follow a transmission schedule			✓	✓
Start transmission at different time instants	✓			
Discovers all neighbors			✓	✓
With feedback mechanism			✓	✓

time, and neither GPS nor other location mechanism or mobility is necessary. According to the simulation results, the proposal behaves properly even in the case that previous knowledge of certain parameters is not available. As for the accuracy, it increases when the number of neighbors decreases, while the time to obtain a full estimate grows. Furthermore, the protocol can properly work in different node mobility, when the network fails or a node joins the network.

A cross-layer protocol, known as ND_HC, for large-scale wireless networks, is presented in [24], which brings together TDMA, network clustering and GPS to carry out the discovery. The MAC layer produces the hello messages and they are sent in a TDMA manner with the aid of hexagonal clusters to improve the performance. An advantage is that this protocol reduces the collisions and improves the throughput. Simulation results through NS-2 allow to conclude that the proposal outperforms the ND_802.11 in terms of discovery efficiency and delay bounds, and effectiveness in finding neighbors.

In [25], the discovery mechanism is modeled as a learning automaton. The nodes learn about their environment from prior knowledge and behaves well in networks composed of a huge number of nodes. The discovery protocol in [25] is based on a learning automata (FLA). Each node includes a steerable directional antenna used to either transmit or listen following an ALOHA-like manner with the same probability. The protocol considers the collisions and knowledge of previously discovered neighbors, achieves a high discovery probability. A reinforcement action describing reward or penalty is chosen by the automaton. Simulation results allows to conclude that the proposal outperforms the 2-way random algorithm [26] and the scan based algorithm [27], regarding the time needed to discover most of the neighbors.

RCI-SBA [28] is a scan based discovery algorithm which integrates radar and communication for ad hoc networks. The devices integrate directional antennas, handles both radar signals and communication signals, and GPS for time synchronization is available. A two-way mechanism is used to carry out the discovery, and when the nodes have to transmit, only the communication signals are transmitted, thus the energy consumption is improved. Numerical results allows to conclude that the proposal can save energy in an efficient manner, whereas simulation results allow to conclude that RCI-SBA outperforms CRA [22] and the scan based algorithm (SBA) [27] in terms of energy consumption.

A neighbor discovery protocol for MANETs is presented in [29], in order to use mobile social applications efficiently. Each device includes a wake-up radio, and a radio transceiver operating in half-duplex mode. A special node, known as sponsor node, is in charge of broadcasting a wake-up radio signal before sending a hello message. The node which receives this signal will change to active state for a hello message sending, therefore a mobile node can discover neighbors which are in active and also in inactive state. Simulations through NS-2 show that the proposal outperforms existing solutions, such as Disco [11], U-Connect [14] and SearchLight [13] regarding the time and energy consumption. In addition, an implementation for smartphone devices is available in [29].

A proactive protocol, known as PWEND, which includes a wake-up mechanism is presented in [30] for MSNs (Mobile Sensor Networks). In PWEND, the discovery may be speeded up by adjusting the broadcast of beacons. In PWEND the parameters can be optimized to achieve the maximum performance. It is proved that the PWEND can achieve the optimal worst-case discovery latency. PWEND is simulated through Matlab, and obtained the energy consumption and latency, allowing to conclude that the PWEND provides better performance than G-Nihao [31], Q-ConnectA [32], Disco [11] and SearchLight (stripe) [13], in terms of the discoveries vs latency metric with duty cycles 1%, 5% and 10%.

[33] presents neighbor discovery tailored for mobile opportunistic networks, which uses mobility awareness. Making use of adaptive beaconing, the protocol reduces the scanning effort. A theoretical analysis evaluates the energy efficiency and data forwarding through simulations taking into account several mobility models.

A survey that addresses continuous neighbor discovery tailored for mobile low duty cycle WSNs is included in [34]. [34] presents continuous neighbor discovery, and discusses the use of U-Connect [14], Disco [11], Hedis and Todis [16], SearchLight [13], PBD [33], and other approaches. It also summarizes the protocols in the literature.

Panacea [35] is an efficient protocol for WSNs, which achieves low latency and energy consumption, taking into account the collisions. According to the results, authors found that there is a bound of $O(N \cdot \ln N)$ in the latency for different duty cycles for Panacea-NCD (no collision detection). When collision detection is possible, in Panacea-WCD there is also a bound in the latency of $O(N \cdot \ln N)$. Moreover, the evaluations match the analysis results.

In this work we propose two deterministic neighbor discovery protocols which achieve to discover all the neighbors, even in dense networks, avoid collisions, and aim at providing a good behavior and performance in static ad hoc wireless network environments. Therefore, our proposals solve the problem of the randomized solutions from the literature, that do not achieve a to discover all the neighbors.

For comparison purposes, we have chosen two randomized protocols available in the literature, and use them as reference, i.e., PRR [5] and the Hello protocol [8].

In Table 2 we compare the reference protocols, i.e., Hello and PRR, and our proposals is presented, so that it highlights the main characteristics of those protocols. Among the features included in Table 2: both reference protocols are randomized and present slots of time, synchronization is required in slot boundaries, and they are appropriate for multi-hop scenarios, they do not achieve to discover all the neighbors. As for our proposals, they are deterministic, they do not present slotted time, they are not asynchronous, they follow a transmission schedule, they are tailored for its use in one-hop environments while the TDMA-based proposal might also be used in a multi-hop scenario although their benefits would be degraded, and both proposals achieve to discover all the neighbors.

3 Deterministic Collision Avoidance Based Proposals

Next, we proceed to present both proposals, i.e., a TDMA-based (with a resulting quadratic neighbor discovery time $O(N^2)$), and a Leader-based (with a resulting linear discovery time $O(N)$).

3.1 Assumptions

The assumptions for the nodes that we must consider for both approaches, are the following:

- They are not allowed to move throughput the deployment area, neither getting in and out of the network nor going in and out of other node's transmission range. Therefore, they are not suitable to be used in MANETs.
- They are randomly deployed once in a delimited area.

- They require synchronization, meaning that they can not work in an asynchronous manner.
- They must transmit following a predetermined schedule.
- They have single identifiers, that allow them to distinguish from other nodes throughout the network, e.g., manufacturer serial number.
- They include a radio transceiver whose transmission range is limited, all the nodes have the same transmission range, and the transceiver allows them to either transmit or receive but not simultaneously, i.e., half-duplex mode is only available.
- They make use of an internal memory, which we refer to as neighbor table.
- The number of nodes N must be known to all the nodes that conform the network.

Regarding its use, the leader-based protocol is tailored for one-hop environments, while the TDMA-based protocol also behaves well in multi-hop scenarios, although the performance would get worse.

Table 2 shows in-depth information about our solutions and the reference protocols.

3.2 Model

3.2.1 Leader-based

The proposal considers the existence of channel collisions, thus its main objective is to avoid them and seek optimal performance.

According to Fig. 1, the model comprises three stages. First, a special type of node, known as leader, is randomly chosen and then it starts the discovery broadcasting its identifier towards its potential neighbors. As soon as the BROADCAST packet reaches its destinations, a second phase begins in which the neighbors must acknowledge to the leader one after another according to a predetermined transmission schedule, in which each neighbor sends an ACK packet with its identifier towards the leader in a fixed duration of N sub-slots, and a different neighbor acknowledges in each sub-slot. As soon as each ACK packet reaches the leader node, it proceeds to update its neighbor table with the neighbor identifier in the packet. When all the acknowledgements have been received, a third stage starts and the leader sends a BROADCAST packet containing the neighbor table built in previous stages and the leader finishes. Moreover, as soon as this last broadcast reaches the neighbors, they proceed to save this table in their local neighbor tables and finish.

With the aim of avoiding collisions due to several nodes transmitting at the same time, in stage 2 the responses to the leader are performed in order, i.e., the neighbors acknowledge

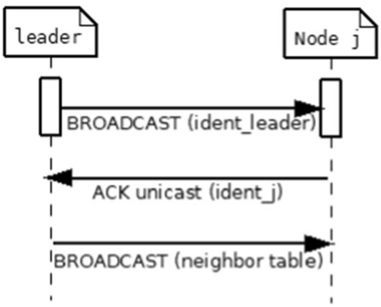


Fig. 1 Leader-based protocol

one after another following a predetermined transmission schedule. Thus, the Leader-based is a collision-free proposal. Also, we found that the time consumption is linear $O(N)$, as we will notice in Sect. 4. However, the Leader-based protocol is tailored for one-hop scenarios, which is an important drawback since it is not allowed its use in multi-hop environments. Moreover, it is only suitable to be used in static environments, meaning that it can not be used in MANETs.

Next, the analytical results obtained for the Leader-based protocol are shown.

The total neighbor discovery time is given in Eq. 1, being N defined as the total number of nodes in the network, and τ defined as the time a node is transmitting.

$$T = (N + 2) \times \tau \tag{1}$$

Therefore, the discovery time follows a linear trend $O(N)$.

The average energy consumption per node is given in Eq. 2.

$$E = \frac{1}{N} \times [(N + 1) \times E_{tx} + (N^2 + N - 1) \times E_l] \tag{2}$$

being E_{tx} the energy consumed by a single node when transmitting per second and E_l the energy consumed by a single node when listening per second.

The average throughput per node is given in Eq. 3.

$$Thr = \frac{N^2 + N - 1}{N \times (N + 2) \times \tau} \tag{3}$$

As for the number of discoveries vs packets sent ratio, it is given in Eq. 4.

$$ratio1 = \frac{N - 1}{N + 1} \tag{4}$$

Finally, we show Eq. 5 for the packets received vs sent ratio.

$$ratio2 = \frac{N^2 + N - 1}{N \times (N + 1)} = \frac{N^2 + N - 1}{N^2 + N} \tag{5}$$

Next, Algorithm 1 shows in detail the operation of the Leader-based proposal.

Algorithm 1 Leader-based proposal

Require: τ time a node is transmitting, N number of nodes in the network

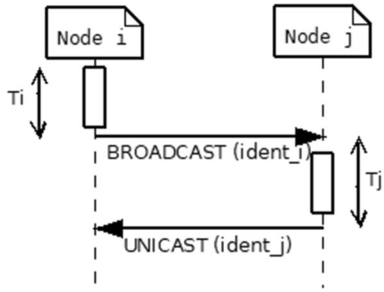
```
1: Randomly choose one leader k
2: k transmits BROADCAST(ident_leader) to the potential neighbors
3: k waits Timer_0 = (N + 1) × τ seconds for the BROADCAST to reach and for the replies from the neighbors
4: for each Neighbor j do
5:    When the BROADCAST reaches neighbor j:
6:       j waits Timer_j = j × τ seconds for its right instant to acknowledge
7:       When Timer_j has expired:
8:       j transmits ACK(ident_j) towards node k
9:    if ACK(ident_j) is received by leader k then
10:      leader k saves ident_j in its neighbor table (NT)
11:   end if
12: end for
13: When Timer_0 has expired:
14: leader k transmits BROADCAST(NT) towards the neighbors and finishes
```

A problem may arise when the broadcast containing the neighbor table is lost, thus the neighbor table will not be received by any neighbor node. In this case, the neighbor discovery fails. An improvement would consist of sending simultaneous unicasts, containing the neighbor table, towards each neighbor.

3.2.2 TDMA-Based

The proposal works in two stages carried out by every node: (1) each node sends a BROADCAST packet, which contains its identifier and reaches all the potential neighbors, and (2) right after receiving the packet, each neighbor acknowledges with a reply ACK packet which contains its identifier and sent towards the sender of the BROADCAST, following a predetermined planned order, in a total duration of N sub-slots; and a different neighbor sends its acknowledgement in each sub-slot. When an ACK is received by a node *i* from the neighbor *j*, the node *i* proceeds to update its neighbor table storing the identifier from node *j*, i.e., $ident_j$.

Fig. 2 TDMA-based proposal



As soon as the ACKs sent by all the neighbors have reached the sender of the BROADCAST, this node finishes the process and the following node, according to the scheduled order, performs stages 1 and 2.

Notice that each node sends a BROADCAST packet one after another, according to a scheduled order which is implemented in the device. The operation can be found in Fig. 2, in which we show two times. First, T_i is the time that a certain node has to wait for its right moment to send the BROADCAST packet, i.e., until the previous nodes have already transmitted their BROADCAST packet and received all the ACK packets. Secondly, each neighbor has to wait a time T_j for its right moment to transmit the ACK packet towards the sender of the BROADCAST, i.e., until the previous neighbors have already transmitted their acknowledgments, and then sends the ACK packets again one after another, according to a scheduled order implemented in the code of the device. The TDMA-based proposal is thus collision-free since all the transmissions are carried out in order following a schedule, so that the collisions are avoided.

Next, those two times T_i and T_j, will be presented.

First, the time T_i that a node i has to wait in order to send the BROADCAST packet is shown in Eq. 6, being T_0 defined as the time the neighbor discovery begins, N defined as the number of nodes, and τ defined the time a node is transmitting.

$$T_i = T_0 + i \times (N + 1) \times \tau \tag{6}$$

Secondly, Eq. 7 shows the time T_j that a neighbor j has to wait in order to acknowledge.

$$T_j = j \times \tau \tag{7}$$

Next, we proceed to show the analytical results for the proposal.

The total neighbor discovery time can be found in Eq. 8.

$$T = N \times (N + 1) \times \tau \tag{8}$$

Therefore, the neighbor discovery time follows a quadratic trend $O(N^2)$.

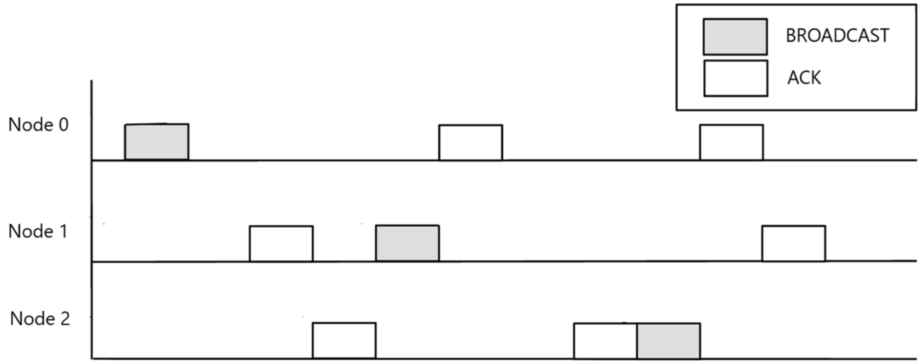


Fig. 3 TDMA-based protocol (timeline)

The average energy consumption per node is given in Eq. 9, being E_{tx} the energy consumed by a single node when transmitting per second and E_l the energy consumed by a single node when listening per second.

$$E = N \times E_{tx} + N^2 \times E_l \tag{9}$$

The average throughput per node is given in Eq. 10.

$$Thr = \frac{N}{(N+1) \times \tau} \tag{10}$$

The number of discoveries vs packets sent ratio is given in Eq. 11.

$$ratio1 = \frac{N-1}{N^2} \tag{11}$$

Next, we show Eq. 12 for the packets received vs sent ratio.

$$ratio2 = \frac{N^2}{N \times N} = 1 \tag{12}$$

In the TDMA-based proposal, the operation of which is shown in Fig. 3, the transmissions of all the nodes, i.e., broadcasts and acknowledgements, are carried out in order so that they avoid the collisions. Therefore, the TDMA-based is a collision-free proposal. However, the neighbor discovery time follows a quadratic trend $O(N^2)$ as shown in Eq. 8, while the discovery time of the Leader-based proposal is better (linear trend $O(N)$).

Next, we present Algorithm 2, which shows in detail how the TDMA-based proposal works.

Algorithm 2 TDMA-based proposal.

Require: T_0 time in which neighbor discovery begins, N number of nodes, τ time a node is transmitting.

Wait for T_0 seconds to begin the neighbor discovery
for each $Node\ i$ **do**
  $T_i = T_0 + i \times (N+1) \times \tau$
  i waits T_i seconds until its transmission moment
  i sends $BROADCAST(ident_i)$ to the potential neighbors
  for each $Neighbor\ j$ **do**
    When $BROADCAST(ident_i)$ reaches neighbor j:
      $T_j = j \times \tau$
      j waits $Timer_j = T_j$ seconds for its right moment to acknowledge
      When $Timer_j$ has expired:
        j transmits $ACK(ident_j)$ towards node i
    When $ACK(ident_j)$ reaches node i:
      i saves $ident_j$ in its neighbor table.
  end for
end for

3.3 Reference Protocols

For comparison purposes, we chose to protocols from the literature.

The Hello protocol presents slotted time of width ω, known as rounds, and in each round every node randomly chooses a time t_i ($0 \leq t_i \leq \omega - \tau$) and broadcasts a packet beginning in t_i during a duration τ and listens for the rest of the slot. When a successful transmission occurs, we say that a neighbor has been discovered. A number of rounds after which the protocol finishes, has to be chosen. Notice that the protocol is one-way.

The PRR protocol also presents slotted time (rounds) of width τ. In a round the nodes choose to transmit with probability $\frac{1}{N}$ or listen with probability $1 - \frac{1}{N}$. Again, when a successful transmission takes place, a neighbor discovery occurs, and the number of rounds is a parameter that must be carefully set. PRR is also a one-way protocol.

3.4 Simulation Scenario

In Sect. 4 we compare the performance of the proposals against that for two reference protocols: Hello [8] and PRR [5]. Lots of simulators exist, e.g., OPNET, OMNET++, NS-2, NS-3, QualNet, MobiWan, BonnMotion. In this work, we used the Castalia 3.2 simulator [10], mainly used to validate protocols for WSNs and BANs, and allows us to validate the proposals in static wireless environments.

We set the same parameters for the proposals and reference protocols, setting different network sizes, different collision models, and setting a specific number of rounds for

Table 3 Simulation parameters

	Value
Simulator	Castalia 3.2
Static network	True
Radio model used	CC2420
collisionModel parameter	2
Transmission power used	− 5 dBm
Packet rate	5 packet/s
Packet size	2500 bytes
Round duration Hello	$\omega = N \times \tau$
τ	0.07s
Size one-hop	10mx10m
Deployment	Grid MxM
PRR Number of rounds	$10 \times$ N
Hello Number of rounds	$0.5 \times$ N

the reference protocols since after a determined number of rounds those protocols finish. We also set the round duration for the Hello protocol to $\omega = N \times \tau$, setting τ to 0.07 seconds. Moreover, for Hello we set the duration to 0.5N rounds and for PRR we set the duration to 10N rounds. Both reference protocols are one-way thus no feedback mechanism is implemented.

As for the deployment area, it has been set to 10mx10m in a one-hop fashion and the nodes have been deployed according to $M \times M$ grids. As stated above, we set the collision models making use of a parameter available in Castalia 3.2, i.e., the *collisionModel*. This parameter can be set to the following values: 0 (no collisions), 1 (simplistic model for collisions), or 2 (additive interference model). For most of the Figures, we decided to use the most realistic collision model, i.e., the additive interference model.

Since the neighbor discovery protocols mainly aim at discovering all the neighbors providing a low time consumption, the simulations were performed to obtain the *Neighbor Discovery Time*, and the *Number of Discovered Neighbors*. Furthermore, as the nodes have batteries that limit the device lifetime, we obtained the *Energy consumption*. In addition, we considered interesting to obtain the *Throughput*, the *Discoveries vs packets sent ratio* and the *Packets received vs sent ratio*.

Moreover, we used the ZigBee radio model, i.e., CC2420. For a transmission power of $-5dBm$, E_{tx}, the energy consumed by a single node when transmitting per second is 0.0522J, and E_l, the energy consumed by single node when listening per second is 0.068J.

The parameters that we used to obtain the simulation results can be found in Table 3.

4 Simulation and Results

Next we proceed to present and discuss the results obtained through simulation in a one-hop environment, and compare the results of our proposals with those for Hello and PRR.

4.1 Neighbor Discovery Time

This metric refers to the time it takes a protocol to end.

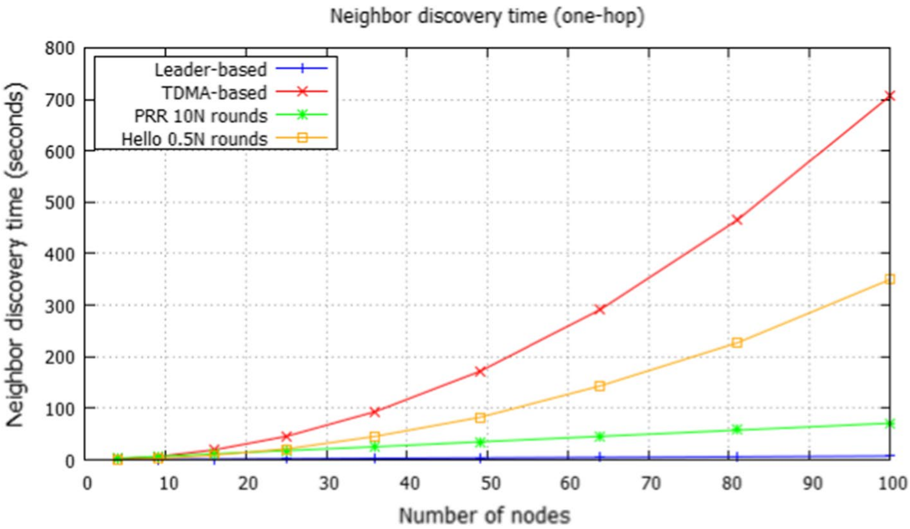


Fig. 4 Neighbor Discovery Time (collisionModel 2)

For the Leader-based proposal, as shown in Sect. 3.2.1, the *Neighbor discovery time* follows a linear trend $O(N)$. As an optimal result, the neighbor discovery time is close to $7s$ for networks composed of 100 nodes.

As for our TDMA-based proposal the discovery time follows a quadratic trend $O(N^2)$, increasing when the number of nodes grows, i.e., worse results than our Leader-based proposal.

Fig. 4 shows the results having set the additive interference model for collisions, i.e., the most realistic collision model, regarding the neighbor discovery time. We can conclude that the Leader-based outperforms the PRR and the Hello protocols, and we can prove that similar results can be obtained for the other two collision models. Next, PRR is better than Hello setting the duration of PRR to 10N rounds, while Hello with 0.5N rounds (slot size N) presents better results than the TDMA-based proposal. The neighbor discovery time for all the protocols presents an increasing trend since as the number of nodes increases, more time is required to discover the neighbors, i.e., the discovery time depends on N.

Moreover, it is demonstrated that the results obtained through simulations match the analytical results presented in Sects. 3.2.1 and 3.2.2, i.e., Eqs. 1 and 8.

4.2 Number of Discovered Neighbors

In this section, three figures are presented and discussed, comparing all four protocols regarding the number of discovered neighbors. Figure 5 shows the results using collision model 0, i.e., no collisions are considered. As for the results for collision models 1 and 2, they are shown in Figs. 6 and 7.

Figure 5 allows us to conclude that all the protocols achieve to discover all the neighbors, i.e, they present an ideal behavior for collision-less model.

As for Fig. 6, it shows the results for collision model 1, i.e., the simplistic model for collisions, in which both proposals manage to discover the N-1 neighbors, outperforming both reference protocols, while Hello 0.5N rounds does not achieve to discover all the neighbors

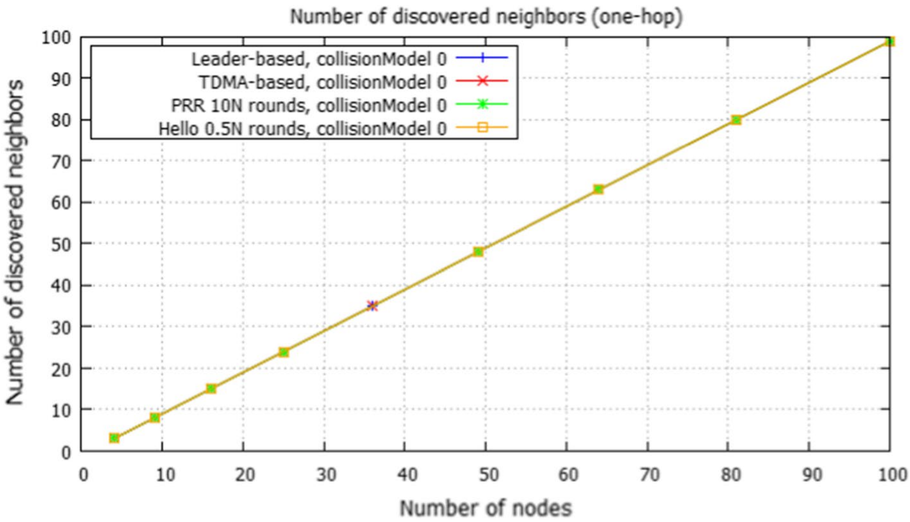


Fig. 5 Number of discovered neighbors (collisionModel 0)

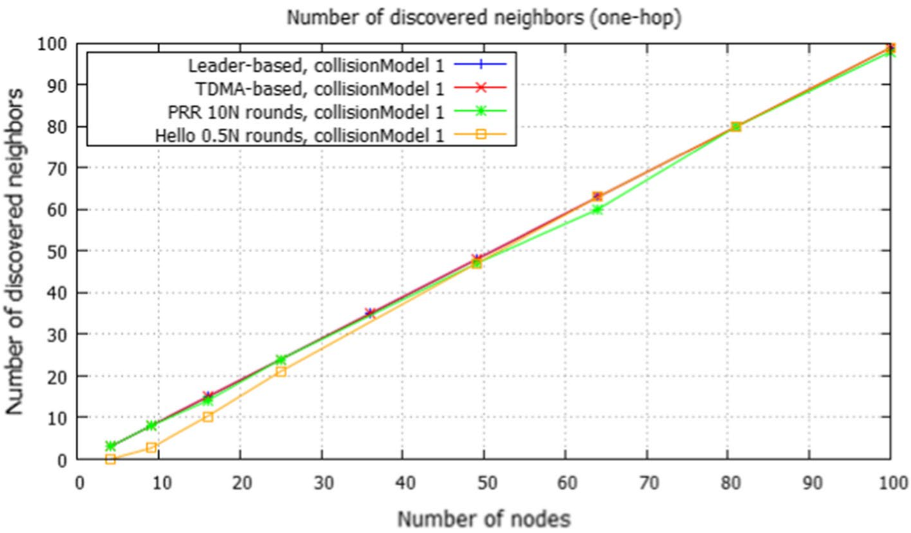


Fig. 6 Number of discovered neighbors (collisionModel 1)

for number of nodes below 50 and PRR 10N rounds does not manage to discover all the neighbors.

Figure 7 shows that, setting the additive interference model for collisions, similar results than those for Fig. 6 are obtained, i.e., the proposals manage to discover the N-1 neighbors, outperforming both reference protocols, while Hello 0.5N rounds does not achieve to discover all the neighbor for number of nodes of nodes below 40, and PRR 10N rounds does not manage to discover all the neighbors.

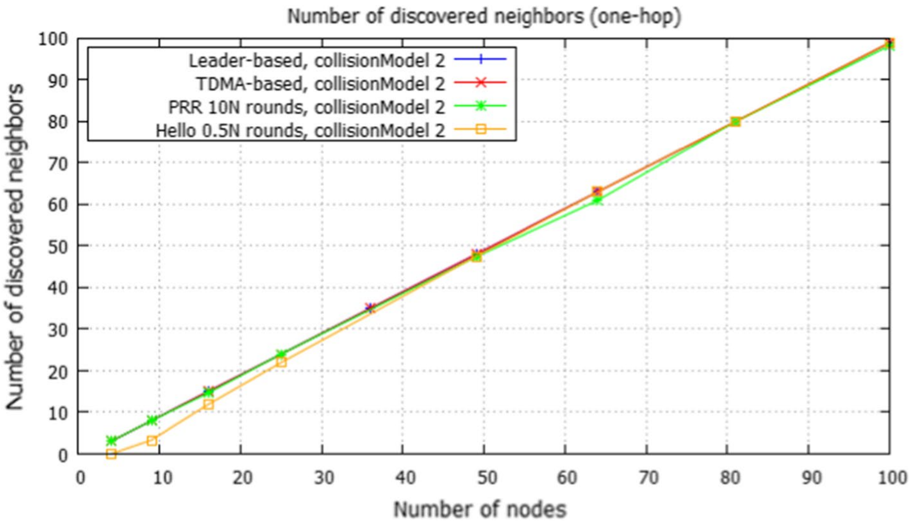


Fig. 7 Number of discovered neighbors (collisionModel 2)

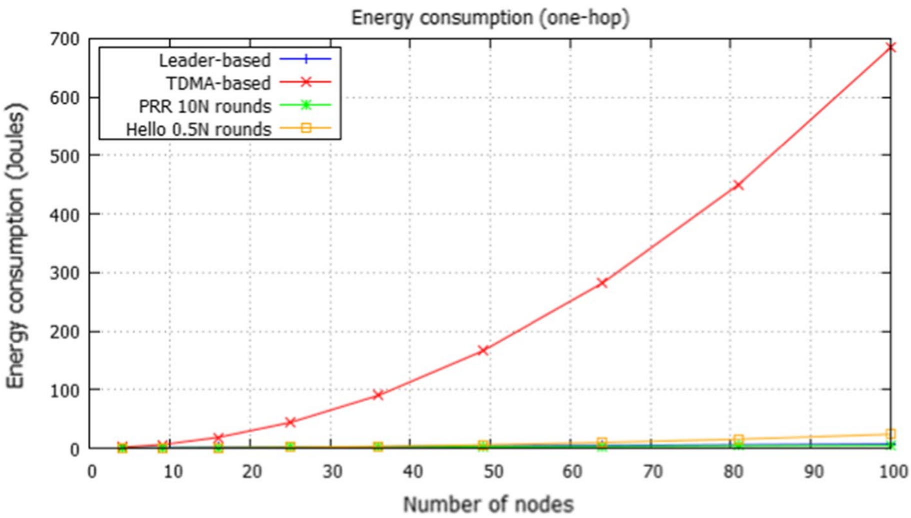


Fig. 8 Average Energy consumption per node (collisionModel 2)

4.3 Energy Consumption

Regarding the energy consumption, according to Fig. 8, all the protocols under test increase the energy consumption as the number of nodes grows, similar to Fig. 4. TDMA-based clearly presents the worst results since more time is required thus the energy consumption is worse, while similar results are obtained for the other solutions. For networks formed by 100 nodes, the PRR 10N rounds is the best, consuming 4.824J per node, then the Leader-based consumes 6.92J per node, and finally the Hello 0.5N rounds consumes 23.734J per

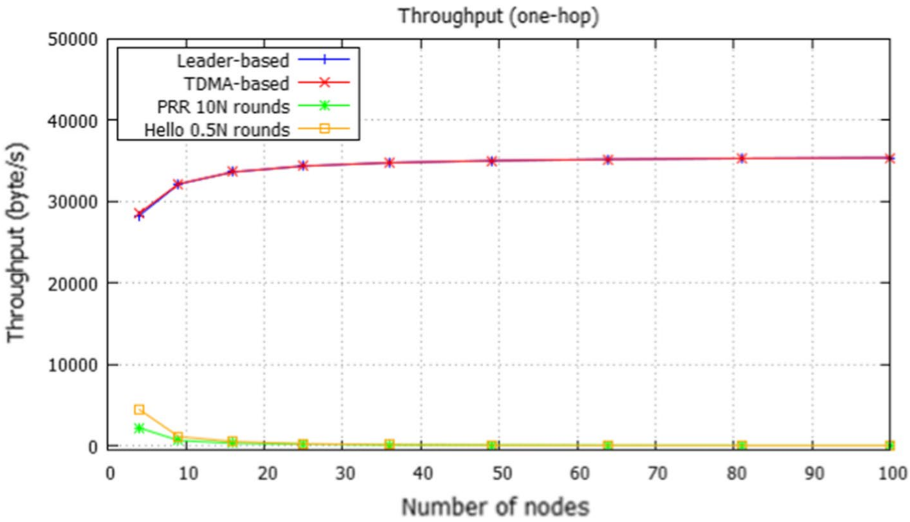


Fig. 9 Average Throughput per node (collisionModel 2)

node. Furthermore, the simulation results closely match the analytical results, shown for the Leader-based in Eq. 2 and for the TDMA-based in Eq. 9 .

4.4 Throughput

As for the Throughput, shown in Fig. 9, both proposals clearly achieve the best results, starting from approximately 28000 byte/s for 4 nodes and converging to 35360 byte/s for 100 nodes, since the packets received per second is the maximum. Then Hello 0.5N rounds outperforms PRR 10N rounds, and both follow a decreasing trend since as the number of nodes grows more collisions appear, less number of packets are received and the time consumption increases and the throughput decreases, Hello 0.5N rounds starts from 4440 byte/s for 4 nodes to 36 byte/s for 100 nodes, while PRR 10N rounds starts from 2200 byte/s for 4 nodes to 38.8 byte/s for 100 nodes. Again, the simulation results match the theoretical values obtained for the Leader-based in Eq. 3 and for the TDMA-based in Eq. 10 .

4.5 Number of Discoveries vs Packets Sent Ratio

As shown in Fig. 10, the Leader-based presents the best results in terms of discovered neighbors vs total packets sent ratio, i.e., optimal, since the time consumption is lower, sending less packets, thus the ratio is higher for the same number of discoveries, and it starts from 0.6 for 4 nodes and converges to 0.98 for 100 nodes. Then, PRR 10N is better than the other solutions for number of nodes above 16, followed by Hello 0.5N rounds, and finally the TDMA-based is the worst. Notice that this order is the same as that for the neighbor discovery time in Fig. 4. Hello 0.5N rounds and TDMA follow a decreasing trend as the number of nodes grows. The simulation results closely match the analytical results in Eqs. 4 and 11.

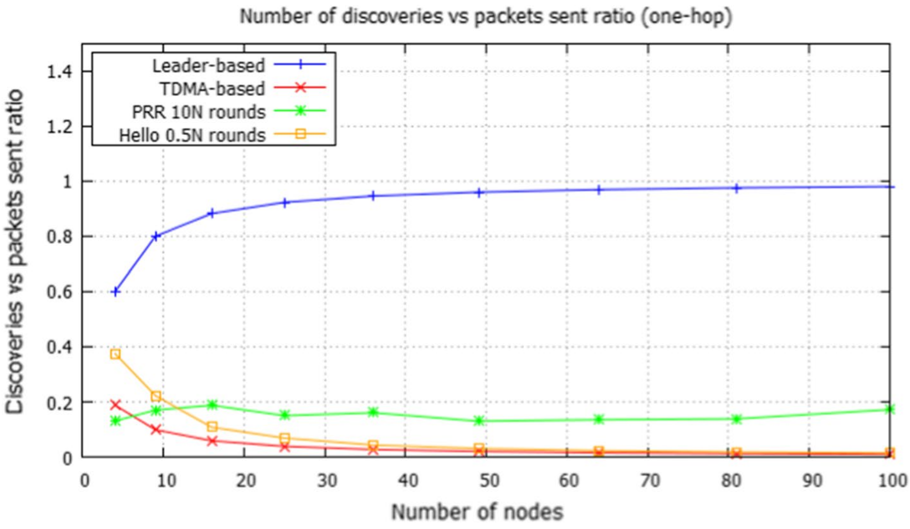


Fig. 10 Discoveries vs total packets sent ratio (collisionModel 2)

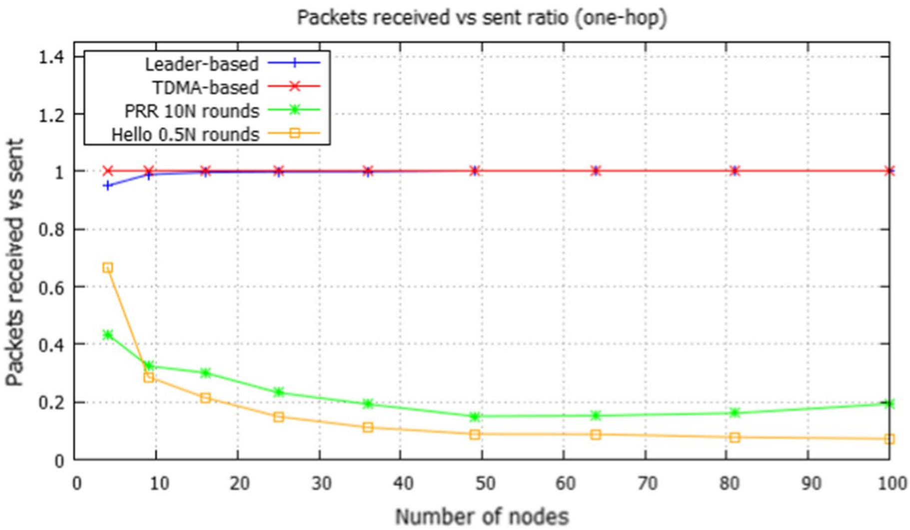


Fig. 11 Packets received vs packets sent ratio (collisionModel 2)

4.6 Packets Received vs Sent Ratio

According to Fig. 11, the TDMA-based proposal outperforms the other solutions, providing a packets received vs sent ratio of 1, i.e., the optimal value, while the Leader-based proposal reaches this value for number of nodes above 10. Next, PRR 10N rounds outperforms the Hello 0.5N rounds, which is the worst. Both reference protocols follow a decreasing trend. Again, the simulation results closely match the analytical results in Eqs. 5 and 12.

5 Conclusion

This work addresses a study of the neighbor discovery problem in static one-hop ad hoc wireless environments taking into account the existence of channel collisions. Hello and PRR have been chosen to be used as reference, and two deterministic proposals have been simulated through Castalia 3.2 for comparison purposes, making use of a feedback mechanism in the proposals to enhance their operation, while the reference protocols are one-way, and obtained six performance metrics.

We also performed an analytical study for both proposals, regarding the neighbor discovery time, the energy consumption, the throughput, the discoveries vs packets sent ratio, and the packets received vs sent ratio.

We found that the Leader-based proposal presents optimal behavior regarding the time results ($O(N)$), and outperforms the PRR with 10N rounds, which in turn outperforms the Hello with 0.5N rounds, and the TDMA-based protocol is the slowest protocol ($O(N^2)$). Thus, the Leader-based protocol achieves an improvement at a factor of N regarding the time consumption over the TDMA-based proposal.

We have also set different collision models, aim at obtaining the number of discovered neighbors, and the results allow us to conclude that both proposals also achieve optimal results and manage to outperform the other solutions.

Regarding the energy consumption, PRR 10N rounds is the best, followed by the Leader-based, which in turn outperforms the Hello 0.5N rounds, and finally the TDMA-based is the worst. As for the throughput, both proposals clearly outperform the reference protocols. The Leader-based proposal presents the best results regarding the discoveries vs packets sent ratio, while PRR 10N rounds is better than the Hello 0.5N rounds and the TDMA-based is the worst. However, TDMA-based presents the best results regarding the packets received vs sent ratio, closely followed by the Leader-based, then PRR 10N rounds and finally Hello 0.5N rounds is the worst.

We found that the Leader-based solution may only properly work in a one-hop environment, although it achieves optimal behavior in static scenarios. As for the TDMA-based proposal, it is also appropriate for multi-hop environments, but in this case its performance would degrade. Both proposals achieve to discover all the neighbors with probability 1, although they rely on a transmission schedule for their operation, and a feedback mechanism is included.

As future research directions we could address the development of new energy-aware protocols in resource constrained multi-hop environments and propose protocols suitable for secure mobile networks. Furthermore, we are interested in researching how protocols behave in indoor environments [36, 37].

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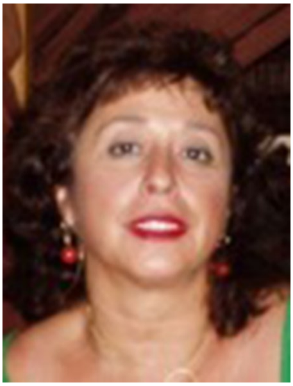

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