

Optimized Asynchronous Multi-channel Discovery of IEEE 802.15.4-based Wireless Personal Area Networks

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Abstract—*Network discovery is a fundamental task in different scenarios of IEEE 802.15.4-based wireless personal area networks. Scenario examples are body sensor networks requiring health- and wellness-related patient monitoring or situations requiring opportunistic message propagation. In this paper, we investigate optimized discovery of IEEE 802.15.4 static and mobile networks operating in multiple frequency bands and with different beacon intervals. We present a linear programming model that allows finding two optimized strategies, named OPT and SWOPT, to deal with the asynchronous and multi-channel discovery problem. We also propose a simplified discovery solution, named SUBOPT, featuring a low-complexity algorithm requiring less memory usage. A cross validation between analytical, simulation, and experimental evaluation methods is performed. Finally, a more detailed simulation-based evaluation is presented, when considering varying sets of parameters (i.e., number of channels, network density, beacon intervals, etc) and using static and mobile scenarios. The performance studies confirm improvements achieved by our solutions in terms of first, average, and last discovery time as well as discovery ratio, when compared to IEEE 802.15.4 standard approach and the SWEEP approach known from the literature.*

Index Terms—Passive discovery, linear programming optimization, mobile communication WPAN, dynamic environments.

1 INTRODUCTION

IEEE 802.15.4-based Wireless Personal Area Networks (WPAN) targeting the interconnection of low-cost, low-rate ubiquitous devices became recently widely used for a plethora of application scenarios. Ubiquitous monitoring [1], [2], health- and wellness-related monitoring [3] are some examples of IEEE 802.15.4-based applications.

Some of these scenarios feature static connectivity patterns, the communication links and multi-hop routes (if any) are established and followed over longer time periods. There are, however, also multiple other cases in which an 802.15.4 WPAN needs to discover other WPANs in their proximity and establish communication with them. As example, we might envision Body Area Networks. Persons equipped with such networks might like to exchange information while passing by – obviously the time to establish the communication

is short. Such a scenario requires very efficient discovery schemata. Designing proper mechanisms especially with respect to the usual requirement of low power consumption creates quite a challenge.

This paper focuses on the problem of how a WPAN having no initial information about the neighborhood can organize fast and energy efficient discovery of other WPANs being agnostic to this process (i.e., the other WPANs do not know that a discovery is going on and do not cooperate in this process). In such case, the WPAN under consideration can only learn about the existence of any neighbor by listening to their beacons. Nevertheless, as neither the channel on which the neighbor operates nor its frequency of beaconing are known, the design of a *listening schedule* determining *when to listen*, *for how long*, and *on which channel* in such a way as to minimize average discovery time is a challenging task. A fast average discovery time is interesting (1) in ubiquitous monitoring applications, where neighbors should be identified by a scanning or surveillance entity, and in (2) DTN (Delay Tolerant Networks) scenarios, where nodes need to find a subset of good forwarders. We will refer to the design of that listening schedule as the *asynchronous and multi-channel passive discovery problem*. The literature does not provide solutions to this problem. The discovery process of related approaches is based on making nodes listen each channel for long time periods. Although providing reliable discovery, they result in long discovery times.

We extend our earlier results [4] and suggest a novel organization of the discovery, following the idea of aggressively changing the channel after short, specifically selected time periods of observation with re-usage of observations made on a given channel. By prioritizing the discovery of neighbors operating with smaller beacon intervals without penalizing the discovery of other nodes, this approach decreases the time to discover the first neighbor and reduces the average time. We use linear programming (LP) to obtain listening schedules that minimize the average discovery time.

The remainder of this paper is structured as follows. Section 2 discusses the related work and Section 3 presents our system model. Section 4 describes the suggested approach and introduces two discovery strategies, named OPT and SWOPT. We compare the performance of these strategies

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TABLE 1: Related works study

	Number of channels	Coordination	Type	Required knowledge
DISCO [5]	single	RX, TX	deterministic	-
U-Connect [6]	single	RX, TX	deterministic	-
Birthday Protocols [7]	single	RX, TX	probabilistic	number of nodes
R. Khalili et al. [8]	single	RX, TX	probabilistic	max. number of neighbors
Quorum-based [9]	single	RX, TX	deterministic	size n of groups
Theis et al. [10]	multi	RX, TX	deter. / prob.	available channels, orthogonal sequence
Arachchige et al. [11]	multi	RX, TX	deterministic	available channels, beacon duration
SWEEP [12]	multi	RX	deterministic	channel set C , sweep set S
IEEE 802.15.4 PSV [13]	multi	RX	deterministic	channel set C , b_{max}
OPT & SWOPT	multi	RX	deterministic	channel set C , set of beacon orders B
SUBOPT	multi	RX	deterministic	channel set C , b_{min} , b_{max}

with the passive discovery of the IEEE 802.15.4 standard and the SWEEP [12] approach. A cross validation between analytical, simulation, and experimental evaluation methods is described in Section 5. In addition, the feasibility of executing the introduced strategies with respect to the features offered by COTS (“commercially available off-the-shelf”) hardware is demonstrated, and the measured performance is compared with data obtained through simulation and analysis. Then, Section 6 investigates in more detail the strategies through simulation and analysis, under varying networking parameters (i.e., number of nodes, number of channels, beacon lengths, beacon losses, etc) in static and mobile scenarios. The results confirm the good performance of our discovery optimization on key metrics as discovery time and probability, even when they are exposed to beacon losses or varying nodes speed. As final contribution, we also propose in Section 7 a low-complexity algorithm, named SUBOPT, which takes into account practical implementation limitations. Finally, Section 8 concludes this paper and describes future work.

2 RELATED WORK

The hereafter discussed neighbor discovery approaches have in common that they divide the time into slots. Two nodes discover each other if both are awake in overlapping time slots. Most neighbor discovery approaches focus on single channel networks. They can be further classified into probabilistic or deterministic approaches. The neighbor discovery protocols presented in [6] [5] are deterministic and based on the selection of prime numbers. Nodes transmit beacons and listen on time slots that are multiples of their prime number. The approach presented in [9] is quorum-based. Time slots are arranged in an $n \times n$ matrix. Nodes pick one column and row in the matrix and stay awake in the selected time slots. Discovery will be achieved at the intersections of the columns and rows.

Probabilistic approaches [7], [14], [8] have in common that nodes select their operational state out of the two states, *transmit* and *listen*, with a predefined probability. In [7], nodes may also select with some probability a state *sleep*. Strategies described in [14], [8] are based on additional feedback. If a node can not receive a beacon due to collisions, it transmits a feedback message. If no feedback is received after transmitting a beacon, the beaconing node assumes that the beacon was successfully received and goes to a passive state.

A lot of research in the multi-channel discovery has been done in the cognitive radio context. In the following, we present different approaches which enable secondary users to perform rendezvous without the use of common control

channels. In [10], four cognitive radio rendezvous approaches are described. The first is a probabilistic approach in which nodes randomly select the operation state and channel. The second is based on generated orthogonal sequences. Nodes performing a rendezvous have to follow the same sequence and will eventually be active on the same channel and in the same time slot, albeit arbitrary delay. The last two approaches use prime number modular arithmetic to guarantee rendezvous. In [11], a leader election protocol to setup a cognitive radio network is presented. A leader is selected based on node IDs and then performs the neighbor discovery by periodically transmitting beacons. Nodes listen on each channel for these announcements and acknowledge the reception.

Contrarily to cognitive radio approaches, the neighborhood discovery in IEEE 802.15.4 networks should not only support (1) multi-channel discovery but also (2) as coordinators may operate with different beacon intervals, an optimized discovery for multiple beacon frequencies. In this category, we can find the IEEE 802.15.4 passive discovery (PSV) [13] and the SWEEP [12] strategy which contrarily to the previously discussed ones, schedule only the listening periods of nodes and take benefit of the periodic beacon transmissions of the MAC. This requires no modifications in the used MAC protocols and allows the usage of MAC implementations in hardware. The paper [12] evaluates the performance of different SWEEP strategies, where the basic idea is making nodes listening subsequently channels for a contiguous time of s slots. The described scanning technique is very similar to PSV, being the only difference the use of different discovery periods of IEEE 802.15.4 passive discovery [13].

Table 1 classifies the various neighbor discovery approaches. The last column of the table shows the initial knowledge required by individual strategies. Compared to PSV, OPT and SWOPT require more information to perform the neighborhood discovery (i.e. set of beacon orders B). The additional knowledge enables the improvement in discovery time of the OPT and SWOPT strategy.

3 SYSTEM DESCRIPTION

Consider a set of n WPANs each having a single coordinator node uniquely identified (e.g., by MAC addresses). Each node is equipped with a single transceiver omni-directional antenna. We assume a half-duplex communication and a multi-channel system. Channels are denoted by the set $C = \{0, \dots, c_{max}\}$ and $|C|$ is the total number of available channels.

Each node is assigned to an operating channel c , randomly chosen from C according to a uniform distribution. Each node

TABLE 2: Summary of the defined parameters

$C = \{0, \dots, c_{max}\}$	Maximum number of channels Set of available channels
z	Number of symbols per time slot
$B = \{b_{min}, \dots, b_{max}\}$	Set of beacon orders
b_{max}	Maximum allowed beacon order
$b_I = 2^b \cdot z$	Beacon interval
[<i>channel</i> , number of time slots]	Sequence of pairs defining a listening schedule
<i>Discovery round</i>	Time required for processing a sequence of pairs provided by a listening schedule.
<i>Sustainability period</i>	Minimum number of slots a node stays listening on a channel.
<i>Discovery time</i>	Time period from when the discovery process started until the first beacon of a node is received.
<i>Discovery probability</i>	Percentage of discovered nodes during the discovery process

is assumed to send beacon signals on its operating channel c at intervals b_I of time. No jitter is considered. Following the IEEE 802.15.4 standard, we consider the *beacon interval* to take one of the values derived by $b_I = 2^b \cdot z$ (where z is a constant), for a *beacon order* $b \in B$. We assume that a set of *beacon orders* $B = \{b_{min}, \dots, b_{max}\}$ is provided, where b_{max} is the maximal allowed beacon order. Nodes are assigned to any beacon order b chosen from B randomly according to a uniform distribution. Note that the use of a set B here allows us to consider the case of nodes operating with different beacon intervals. Such is the case for nodes using different hardware, having varying purpose of use, or being deployed by different vendors. By choosing $B = \{0, \dots, 14\}$ and $z = 960$ the resulting b_I correspond to the IEEE 802.15.4 standard.

Beacons are *only* transmitted on the operating channel c of a node, while data can be sent on any other channel in C . In particular, each node can be in one of the following states:

- *Data communication state*: Data can be sent on any channel in C . Nodes are able to exchange messages if they are using the same channel and are in the communication range of each other.
- *Beaconing state*: The periodic beacon signals are transmitted on the operating channel c .
- *Scanning state*: Nodes listen for beacon signals on channels in C and are not transmitting any signal.
- *Sleeping state*: Nodes mainly switch their radio off.

We consider a completely passive discovery, based exclusively on beacon listening. The listening process uses slotted time. We assume the length of a time slot equals to the smallest beacon interval. This corresponds to the beacon order $b = 0$, i.e., $b_I = 2^0 \cdot z$. When considering the 2.4GHz ISM band of the IEEE 802.15.4 based radios, the constant z corresponds to 960 symbols (i.e., $16\mu s$ per symbol), resulting in the smallest beacon interval of length $15.36ms$. At each node performing the discovery, a *listening schedule* is followed, which can be defined by a sequence of pairs [*channel*, *number of time slots*]. For instance, the listening schedule $[1, 2], [0, 4], [1, 2]$ describes a scan which would listen 2 time slots on channel 1, 4 time slots on channel 0, and then, again 2 time slots on channel 1. We define a *discovery round* as the time needed for processing the sequence of pairs provided by a listening schedule. The minimum number of slots a node stays listening on a given channel is called here a *sustainability period*.

We assume that a node i initially knows: (1) its identity ID , (2) its beacon interval b_I , (3) its operating channel $c \in C$, (3) the set of available channels C , and (4) the set of beacon orders B possibly used in the neighborhood. A node i scanning a channel c discovers current neighbors in c whenever such

neighbors are within the i 's communication range and node i receives their periodically transmitted beacons.

Listening schedules will be evaluated according to the metrics: discovery time and probability. The *discovery time* is the time period from when the discovery process started (i.e., the scanning state of a node started) until the first beacon of a node is received. The average is then computed among the discovery times of all the discovered nodes. Finally, the *discovery probability* describes the percentage of discovered nodes during the discovery process. All the defined parameters are summarized in Table 2.

4 LISTENING SCHEDULE

This section identifies listening schedules that minimize the average discovery time. The idea behind this optimization is to accelerate the discovery of neighbors operating with the smaller beacon orders of the set B at each channel $c \in C$ and to reuse information gained in previously scanned slots.

Hereafter, we provide the theoretical formulation and the linear programming model of the asynchronous multi-channel neighbor discovery problem. Then, we present two resulting discovery strategies and finally, discuss implementation issues related to the considered assumptions of the LP model in order to provide more realistic solutions.

4.1 Neighbor discovery optimizations

This section details the notion of *listening schedule* performed by nodes in scanning state and presents its optimization.

4.1.1 Theoretical formulation

The *listening schedule* determines the periods of time that each node spends on one particular channel, listening for periodically sent beacons. Scanning nodes start listening at time slot t_0 . The schedule involves assigning to each node in the scanning state binary variables $x_{c,t}$, for all $c \in C$ and $t \in T$, describing whether a node performs a scan on channel c at time slot t :

$$x_{c,t} = \begin{cases} 1, & \text{if a scan is performed on channel } c \text{ at time slot } t \\ 0, & \text{otherwise} \end{cases}$$

The latency required for a node to perform total discovery of neighbors operating with B and on C is defined as $t_{max} = |C| \cdot 2^{b_{max}} - 1$, assuming no beacons losses. The set of time slot indexes can be then represented by $T = \{t_0, \dots, t_{max}\} = \{0, \dots, |C| \cdot 2^{b_{max}} - 1\}$. The next section presents the LP model providing optimized listening schedule.

4.1.2 Optimization model

Let us first consider a simplified case under the following assumptions:

- *No channel switching time*: switching between channels is performed instantaneously;
- *No beacon transmission/reception time*: beacon length is assumed to be zero;
- *No beacon losses*: no collision is considered and channel conditions are ideal (e.g., no interference or fading).

We will demonstrate that under these assumptions it is possible to formulate our discovery problem as a linear program, with reasonable number of decision variables. The assumptions are only considered in the LP problem presented in this section and are not used in the evaluations presented in Sections 5 and 6.

We formulate the LP problem minimizing the average discovery time under the following constraints:

- 1- *Number of scanning time slots per channel*: The number of time slots per channel for a scanning node to perform the total neighbor discovery can not be less than $2^{b_{max}}$. Otherwise nodes using the maximum beacon order b_{max} may not be discovered:

$$\forall c \in C \sum_{t=t_0}^{t_{max}} x_{c,t} \geq 2^{b_{max}} \quad (1)$$

- 2- *No concurrent scanning*: A node can not scan more than one channel at each time slot:

$$\forall t \in T \sum_{c=0}^{c_{max}} x_{c,t} \leq 1 \quad (2)$$

- 3- *Allocation of time slots*:

The time slots to be scanned should be allocated in such a way that each slot belonging to a beacon interval b_I is scanned at least once. Due to the periodicity and multiplicity of the beacon intervals, information gained from previous scanned slots on a channel can be reused to avoid unnecessary scans. For instance, if a scanning node is searching for neighbors with $b_I = 2^2 \cdot z = 4 \cdot z$ and has already performed a scan at time slots 0, 2, and 3 on channel c , it has only to scan one additional time slot $t_{4 \cdot i + 1}$ for any $i \in \mathbb{N}$, to detect all nodes using $b_I = 4 \cdot z$:

$$\forall c \in C \forall b \in B \forall \delta \in \{0, \dots, 2^b - 1\} \sum_{i=0}^{c_{max}} x_{c, 2^b \cdot i + \delta} \geq 1 \quad (3)$$

Furthermore, this equation constraints the assignment of the variables $x_{c,t}$ into groups for each beacon order. On one hand, this grouping enables the idea behind the optimization of discovering nodes with smaller beacon orders first. On the other hand, it allows a linear formulation of the optimization goal, as explained in detail hereafter. If the scan of a group for a specific beacon order has finished, all neighboring nodes with this beacon order should have been discovered, under the assumptions of the optimization model. The search for nodes with the next higher beacon order in set B can then start. Clearly, in the discovery process for a specific beacon order b , there may be also nodes discovered with larger beacon order than b . Due to the structure of the beacon intervals, the

information gained by previous scanned slots can be reused and therefore, shorten the scan duration to discover nodes with larger beacon orders. The beacon order grouping is further explained with an example in Section 4.1.3.

The goal of *minimizing the average discovery time by computing the discovery probability for any time slot* results in non-linear formulation. In fact, the probability of discovering a node with beacon order b on channel c in time slot t depends on which slots have already been scanned on channel c in previous attempts. If a time slot has not scanned before, the probability to discover a node operating with beacon order b on a channel $c \in C$ is $P_b(b) = \frac{1}{2^b \cdot |C|}$. For instance, assuming only one channel and only nodes with beacon order $b = 1$, i.e. there exists only two slots between two consecutive beacons, the probability to discover such a node is 50% in the first and 50% in the second time slot. However, there will be no new discoveries in the other time slots and therefore the discovery probability for these time slots is zero. Thus, $x_{c,t}$ would be dependent on past $x_{c,\tau}$ with $\tau < t$. Such non-linear models are usually far more difficult to solve than corresponding linear model [15].

We propose to take advantage of the structure of the considered beacon interval, i.e. $2^b \cdot z$, and to deal with the non-linear optimization complexity by defining groups of time slots for each beacon order b as already used in Eq. 3. In this way, the discovery probability for nodes with a given b is the same for all time slots in the defined b group, which allows a linear formulation. The size of a group depends on the corresponding b and the number of channels $|C|$ (as given by the two sums in the bracket of the Eq. 4).

Finally, the linear formulation of the objective function that minimizes the average discovery time follows:

$$\min \frac{1}{|B|} \sum_{b_j = b_{min}}^{b_{max}} \begin{cases} \sum_{t=0}^{2^{b_j} \cdot |C| - 1} \sum_{c=0}^{c_{max}} u(c, t, b_j), & \text{if } b_j = b_{min} \\ \sum_{t=2^{b(j-1)} \cdot |C|}^{2^{b_j} \cdot |C| - 1} \sum_{c=0}^{c_{max}} u(c, t, b_j), & \text{otherwise} \end{cases}$$

with $u(c, t, b_j) = x_{c,t} \cdot (t \cdot z + 0.5 \cdot z) \sum_{p=b_j}^{b_{max}} \frac{1}{2^p \cdot |C|}$ (4)

The intuitive explanation of Eq. 4 follows. The average discovery time is computed for all beacon orders in B (cf. 1st sum). The time slots t are grouped. The first and the last time slot of these groups depend on the current beacon order b and the number of channels $|C|$ (cf. 1st sum in the bracket). Furthermore the average discovery time is computed for all channels in C (cf. 2nd sum in the bracket). As mentioned before, the probability of discovering a node with beacon order b is the same for all time slots in one group. In order to consider the fact that in average, nodes are discovered in the middle of each time slot, the discovery time is set to $(t \cdot z + 0.5 \cdot z)$. Finally, the probability of discovering a node in a slot depends on its beacon order and the number of channels (cf. last sum). The intuition here is that lower beacon interval of a node leads to higher probability of finding this node in one particular slot. At the best of our knowledge, *this is the*

first linear programming model for the asynchronous multi-channel discovery problem.

For solving specific LP problems, the modeling language ZIMPL [16] is used to translate the mathematical models into linear programs, which are then solved with CPLEX 9.0 [17].

4.1.3 Example

This section provides an example for the grouping of the time slots applied in the LP model in Eq. 3 and 4. In this example, the following channel set $C = \{0, 1\}$ and the beacon order set $B = \{0, 1, 3\}$ are used. Table 3 shows the resulting time slot indices of variable $x_{c,t}$ for each beacon order. The channel index c is not specified in order to reduce the size of the table. However, the resulting time slot indices are valid for all $c \in C$.

For beacon order $b = 0$ the time slot index set contains 0 and 1, for $b = 1$ it goes from 0 to 3 and for $b = 3$ from $\{0, \dots, 15\}$. This defines the groups for each beacon order and follows the idea of discovering nodes with lower beacon orders first. In fact, to discover all nodes operating with $b = 0$ only 2 time slots are required; 4 time slots are required when $b = 1$; and 16 time slots (the complete schedule) when $b = 3$.

The table also shows the completeness of the scans for the beacon orders. Eq. 3 constrains the listening schedules to such solutions in which each sub slot of a beacon interval for each beacon order b is scanned at least once. For each beacon order b and for each of the corresponding $\delta \in \{0, \dots, 2^{b-1}\}$, there has to be at least one $i \in \{0, \dots, c_{max}\}$ so that the resulting $x_{c,2^{b \cdot i + \delta}}$ is set to one. In Table 3 the resulting $x_{c,t}$ variables are separated by dotted lines. Eq. 3 enforces that for each beacon order b one $x_{c,t}$ in these groups has to be set to one.

Table 4 shows the bounds of the summations of Eq. 4 using the mentioned parameter sets. The time slots are again split up into three groups: The first group from time slot 0 to 1, the second from 2 to 3 and the last from 4 to 15 (t -Sum). After the first group is finished, all nodes operating with $b = 0$ are discovered, then, after the second group, all nodes with $b = 1$ are discovered, and finally, at the end of the scan, nodes with $b = 3$ are discovered. Therefore, for the first group, the probability computation is applied to all three beacon orders, for the second group only to $b = 1$ and to $b = 3$, and for the last group to $b = 3$ (p -Sum). This matches the time slot indices assignment of the $x_{c,t}$ variables of Eq. 3 (see Table 3).

4.2 Neighbor discovery strategies

We propose two strategies for the discovery problem:

- *OPT strategy*: This strategy leads to listening schedules when considering a sustainability period of one time slot, corresponding to the smallest beacon interval: i.e., $b_I = 2^0 \cdot z$. Although improving the neighbor discovery time, OPT leads to a scheduling based on a higher number of switches among channels than SWOPT (cf. Figure 1(a)).
- *SWOPT strategy*: In this strategy we increase the sustainability period to $2^{b_{min}} \cdot z$, corresponding to the beacon interval given by the minimum beacon order of the considered set B . This is proposed to reduce the number of channel switches of the OPT approach. In the example pictured in Figure 1, the number of channel switchings is reduced from 8 to 5. The level of reduction depends

TABLE 3: Example showing the resulting time slot indices of Eq. 3 using $C = \{0, 1\}$ and $B = \{0, 1, 3\}$

c	δ	i	$x_{c,2^{b \cdot i + \delta}}$		
			$b = 0$	$b = 1$	$b = 3$
{0,1}	0	0	$x_{c,0}$	$x_{c,0}$	$x_{c,0}$
{0,1}	0	1	$x_{c,1}$	$x_{c,2}$	$x_{c,8}$
{0,1}	1	0		$x_{c,1}$	$x_{c,1}$
{0,1}	1	1		$x_{c,3}$	$x_{c,9}$
{0,1}	2	0			$x_{c,2}$
{0,1}	2	1			$x_{c,10}$
{0,1}	3	0			$x_{c,3}$
{0,1}	3	1			$x_{c,11}$
{0,1}	4	0			$x_{c,4}$
{0,1}	4	1			$x_{c,12}$
{0,1}	5	0			$x_{c,5}$
{0,1}	5	1			$x_{c,13}$
{0,1}	6	0			$x_{c,6}$
{0,1}	6	1			$x_{c,14}$
{0,1}	7	0			$x_{c,7}$
{0,1}	7	1			$x_{c,15}$

TABLE 4: Example showing the resulting bounds of the summations of Eq. 4 using $C = \{0, 1\}$ and $B = \{0, 1, 3\}$

c	b_j	t -sum		p -sum	
		low. bound	up. bound	low. bound	up. bound
{0,1}	0	0	1	0	3
{0,1}	1	2	3	1	3
{0,1}	3	4	15	3	3

on the number of channels and on the difference between the maximum and minimum beacon order. We name this strategy *SWOPT*, *SWitched OPTimized* (cf. Figure 1(b)).

In this paper, we compare the schedules resulting from OPT and SWOPT to the schedules generated by two passive discovery strategies in the literature: the IEEE 802.15.4 standard [13], named *PSV*, and the *SWEEP* approach [12]. The PSV strategy requires listening for a period corresponding to the maximum beacon order b_{max} on each channel of C (cf. Figure 1(c)). The knowledge of C and b_{max} is sufficient to discover all nodes operating with a beacon order lower than b_{max} . On the other hand, the SWEEP strategy leads to a simple listening schedule composed by a set of k subsequent sweeps (i.e. $S = \{s_1, s_2, \dots, s_k\}$). At each sweep, s_i time slots are spent on each channel: Nodes listen subsequently channels for a continuous time of s_i slots, starting from the first channel (cf. Figure 1(d)). Sweeps are determined based on the beacon order set B . Here, nodes are required to have the knowledge of the set of sweeps S and channel C .

Figure 1 depicts the scanning schedules resulting from all four strategies, when considering $C = \{0, 1, 2\}$ and $B = \{1, 2\}$. It is worth noting that, contrarily to SWEEP, the OPT and SWOPT strategies result in the same total number of listening time slots than PSV (i.e., 12 time slots for this example). This shows OPT and SWOPT do not impose any additional overhearing energy consumption compared to the IEEE 802.15.4 standard. Besides, OPT and SWOPT present a significant improvement in terms of discovery time for all beacon orders smaller than b_{max} (as discussed in next sections). On the other hand, SWEEP requires more time slots to perform the required discovery than the other strategies, for any set of $|B| \geq 2$. In the example used in Figure 1, SWEEP

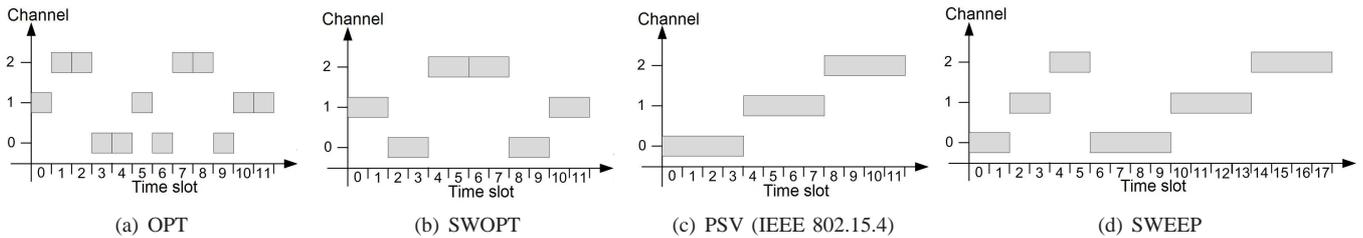


Fig. 1: Distribution of scanning time slots for $|C| = 3$ and $B = \{1, 2\}$

requires 18 time slots instead of 12 to discover nodes.

4.3 Coming closer to reality

In order to provide more realistic solutions, this section discusses implementation issues related to the assumptions considered in Section 4.1.2 and their impact on all the discussed strategies (i.e., OPT, SWOPT, PSV, and SWEEP) as well as some countermeasures. In Section 6, we show that simulation results implementing such countermeasures are in good agreement with analytical results.

4.3.1 Imperfect knowledge of C and B

The complete knowledge of the required parameters (i.e., C , B , or b_{max}) may not be available. Such imperfect knowledge may affect the discovery probability and time resulted from the discussed strategies.

In particular, a node will not be discovered if it operates on a channel $c \notin C$ or might not be discovered if it operates with a beacon order $b > b_{max}$. On the other hand, the probability to discover nodes will not be affected if there is (1) any channel in C not used by such nodes or (2) any node using a beacon order $b < b_{max}$ for $b \notin B$. Nevertheless, the time to discover those nodes operating on the used channels or those with such beacon orders might increase.

4.3.2 Channel switching time

In real systems a RF transceiver needs some time in order to switch from one channel to another, before it can start transmitting and receiving on the new channel. Therefore, the channel switching time may have an impact on the discovery time and probability. In the following we present and evaluate three approaches.

1st approach: The first approach requires performing the channel switching after listening a complete time slot if the next listening slot is allocated on a different channel. Executing the channel switching at the end of a time slot results in a time shift of the computed scanning schedule at each channel switching.

2nd approach: This approach requires shortening the listening time of each scanning slot by the channel switching time if and only if the following slot is allocated on another channel. This avoids a shift of the scanning schedule, but reduces the listening periods of the scanning slots. Beacon transmissions that start within the switching period can not be received. Repeating the discovery schedule will again lead to miss these beacons due to their periodicity, disregarding clock skew on the nodes.

3rd approach: In order to avoid a time shift of the schedule caused by the 1st approach and the deaf periods of the 2nd approach, the listening time of the slots is shortened by the channel switching time in the following way. When the discovery round (see Section 3) is even, the listening time is shortened at the end, otherwise, at the beginning. The alternation of the shortenings allows the discovery of beacon transmissions that start within the switching period.

The approaches are evaluated according to the average discovery time and the discovery probability. For the sake of evaluation, the listening schedule has been repeated until the discovery probability between two consecutive rounds has not changed. Table 5 shows analytical results for the three approaches and non-realistic case of “no switching time” (see Section 5.1 for the methodology). The following parameters were used: $|C| = 16$, the beacon order set $B = \{4, 5, 6, 7, 8, 8, 10, 11\}$, a beacon frame of zero length, and a channel switching time of 19 symbols.

Using the 1st approach the average discovery time of the OPT strategy is only half and the SWOPT strategy one third of the time required by the PSV strategy. Due to the high number of channel jumps of the OPT strategy and the appending of the channel switching time at the end of the listening slots, the computed discovery schedule is getting shifted. This result in a worse average discovery time for the OPT strategy than the SWOPT strategy, even if both has the same theoretical results.

Using the 2nd approach, OPT and SWOPT have almost the same average discovery time which is one fourth of the time required by the PSV strategy. Nevertheless, due to the higher number of channel switchings compared to PSV, OPT and SWOPT are more affected by the shortening of the listening time executed by the 2nd approach. On the other hand, the discovery probability of SWEEP is not impacted by this time shortening because of its higher number of listening time slots. It is worth noting the approaches have almost no influence on the average discovery time of the PSV and SWEEP strategies, as they are changing the channel only a few times.

Finally, the channel switching time management resulted from the 3rd approach provides the best combination between average discovery time and complete discovery, which justify its use in the further evaluation of the strategies.

4.3.3 Beacon transmission/reception time

Due to the limited channel bandwidth, the transmissions of beacons take time and the size of the beacons may have an impact on the scanning schedule. If a beacon is received shortly before a scheduled channel switching and the beacon

TABLE 5: Analytical results for approaches dealing with channel switching

	PSV		SWEEP		OPT		SWOPT	
	Avg Disc.	Disc. Prob.						
	Time (s)		Time (s)		Time (s)		Time (s)	
1st ap.	239,85	1,0000	90,81	1,0000	121,53	1,0000	87,92	1,0000
2nd ap.	239,85	≈ 1	90,80	1,0000	63,23	0,9839	62,72	0,9990
3rd ap.	239,85	1,0000	90,80	1,0000	68,53	1,0000	63,01	1,0000
No s. t.	239,85	1,0000	90,78	1,0000	62,67	1,0000	62,67	1,0000

reception is not cancelled, the subsequent discovery schedule will be delayed. Thus, we assume an implementation that shortens the listening time of the next scanning slot by the delay caused by such reception.

4.3.4 Beacon losses

The reception of beacons of neighboring nodes might be impacted by nodes mobility and losses, what may also increase the discovery time and decrease the discovery probability. Therefore, the general approach will be to repeat the listening schedules. The frequency of repetitions will depend on the current network conditions.

5 EVALUATION METHODS

A cross validation between analytical, simulation, and experimental evaluation methods is performed throughout this section. Such methods as well as the obtained results are detailed in the following sub-sections. The comparison choice with PSV and SWEEP strategies is due to the similarities of operating conditions among the strategies, like: multi-channel support, asynchronous and passive discovery.

5.1 Analytical method

This section provides an analytical evaluation of the *discovery probability* and *average discovery time*. The analysis is applied to the listening schedules $x_{c,t}$ derived from any of the considered strategies (i.e., OPT, SWOPT, PSV, and SWEEP), under the assumption that beacon length is neglected.

The analytical model consists of the computation of the probability $P(b, c, t)$ of discovering a node at time slot t operating with beacon order b on channel c . In particular, when using the listening schedule described by the variables $x_{c,t}$, the probability $P(b, c, t)$ can be computed as follows:

$$P(b, c, t) = P_b(b) \cdot P_c(b, c, t) \cdot x_{c,t} \quad (5)$$

$P(b, c, t)$ depends on the operating conditions of a node (cf. Eq. 7), on the required time for channel switching, on the previous scans and channel conditions (cf. Eq. 10) as well as on the listening schedule $x_{c,t}$. Nodes choose their beacon order b and channel c randomly according to uniform distribution. Assuming that the conditions on the channels are equal, the probability $P_c(b, c, t)$ is not dependent on the probability $P_b(b)$ resulting from the operation conditions of a node.

Before detailing each one of these issues, the parameter $s(t)$ is introduced. After obtaining a listening schedule from the optimization, one has to determine how to deal with the channel switching time. The parameter $s(t)$ describes whether or not there will be a channel switching in time slot t .

$$s(t) = \begin{cases} 1, & \text{if listening time is shortened in time slot } t \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Operating conditions of nodes: The probability to discover a node operating with beacon order b on a channel $c \in C$ can be computed as:

$$P_b(b) = \frac{1}{2^b \cdot |C|} \quad (7)$$

Channel switching time and channel conditions: $P(b, c, t)$ is also dependent on the channel switching time, on the beacon loss probability p_l , and on the number of previous scans of *similar* slots, referred as $S(b, c, t)$.

An example of *similar* slots follows. Consider a listening schedule scanning four successive slots on channel c , starting at time slot 0 (e.g., as shown in Fig. 1(c)). For beacon order $b = 1$ (i.e., $b_I = 2^1 \cdot z$), slots 0 and 2 as well as 1 and 3 are *similar*: (i) $S(1, c, 0) = 0$ and $S(1, c, 2) = 1$ and (ii) $S(1, c, 1) = 0$ and $S(1, c, 3) = 1$. Let function $S(b, c, t)$ represent the number of *similar* time slots already scanned (i.e. from 0 to $t - 1$ time slot), for channel c and beacon order b .

Depending on the handling of the channel switching time, the listening time of previously scanned *similar* slots may have been shortened. Therefore, we have to differentiate the *similar* slots between complete scanned slots and slots in which the listening time was reduced due to channel switching. $S(b, c, t)$ computes the sum of all previous scanned *similar* slots despite possible listening time reduction. In contrast, $S_c(b, c, t)$ adds up only these previous scanned *similar* slots that were completely scanned.

$$\begin{aligned} S(b, c, t) &= \sum_{i=0}^{\lfloor \frac{t}{2^b} \rfloor - 1} x_{c,\tau} \\ S_c(b, c, t) &= \sum_{i=0}^{\lfloor \frac{t}{2^b} \rfloor - 1} x_{c,\tau} \cdot (1 - s(\tau)) \end{aligned} \quad (8)$$

with $\tau = 2^b \cdot i + (t \bmod 2^b)$

If the loss probability p_l is 0, the probability of detecting a node $P_c(b, c, t)$: (i) is 1 if no similar slots have been scanned before (i.e. $S(b, c, t) = 0$), or (ii) is 0 if $S(b, c, t) > 0$.

On the other hand, if the loss probability p_l is larger than zero, the scan of *similar* slots multiple times increases the detection probability. Assuming only completely scanned time slots without any reduction due to scheduled channel switching times, the detection probability can be computed as follows:

$$P_l(b, c, t) = p_l^{S(b, c, t)} \cdot (1 - p_l) \quad (9)$$

Similar slots have to be treated differently if a channel switching time larger than zero is assumed. The shortening of the listening time to perform the channel switchings results in differently scanned similar slots. Assuming the reduction of listening time (due to a scheduled channel switching of duration γ symbols) is always performed in the same part of a time slot of length z symbols, the probability can be computed in the following way:

$$P_c(b, c, t) = \frac{z - \gamma}{z} p_l^{S(b, c, t)} \cdot (1 - p_l) + (1 - s(t)) \cdot \frac{\gamma}{z} p_l^{S_c(b, c, t)} \cdot (1 - p_l) \quad (10)$$

The first addend of Eq. 10 computes the probability for the major part of the time slot ($\frac{z-\gamma}{z}$), which is never affected by the channel switching time reduction. The second addend deals with the possibly shortened part ($\frac{\gamma}{z}$). If $s(t)$ equals to one, meaning that the listening time of the current slot is shortened, the computation includes only the non-affected part. Otherwise, if no channel switching is scheduled ($s(t) = 0$), we also have to consider the minor part, which may have been reduced in previously scanned *similar* slots and therefore, apply $S_c(b, c, t)$.

If the allocation of the listening time reduction within a time slot is changing (e.g., as described in Section 4.3.2 for the 3rd approach), the number of previous scans has to be summed up separately for each possible allocation within a time slot. Furthermore, Eq. 10 has to be adapted accordingly.

Finally, the average time to discover all nodes operating with a beacon order b on a channel c (respectively selected randomly according to a uniform distribution from sets B and C) is the sum of the probabilities $P(b, c, t)$ multiplied by the time of the discoveries, assuming that in average, nodes are discovered in the middle of a time slot (i.e., at $t \cdot z + 0.5 \cdot z$).

$$\sum_{t=0}^{t_{max}} \sum_{c=0}^{c_{max}} \frac{1}{|B|} \sum_{b=b_{min}}^{b_{max}} (t \cdot z + 0.5 \cdot z) \cdot P(b, c, t) \quad (11)$$

5.2 Simulation method

The OMNeT++ 3.3 discrete event simulator [18] is used here together with the Mobility Framework (MF) [19] and a model of the IEEE 802.15.4 PHY and MAC layer. The success of reception is computed as follows. First, the received power of incoming frames is checked against a sensitivity threshold. If the power level is sufficient, the noise level is recorded during the duration of reception. Received powers of simultaneous interfering transmissions from other nodes are added to the noise level. After receiving is completed, the minimum SNR recorded during the time of reception is checked against a threshold value and thus, verified if the packet can be successfully received.

Friis equation is used to compute the path loss. In order to avoid erroneous values at small distances, especially for distances less than the wavelength λ , the path loss computation uses a linear slope between zero distance and a reference distance of 1 meter. For distances larger than the reference distance, the path loss is computed using Friis transmission equation with a path loss coefficient of $\alpha = 2$.

The detailed setup considered in the simulation scenario is described in Section 6.1 using the parameters described in Table 7. Note that only static scenario is considered for the cross validation of the strategies (cf. Section 5.4). A more detailed simulation evaluation is performed in Section 6.1, where mobility is also considered.

5.3 Experimental method

In the experimental evaluation, the discovery strategies are evaluated using the Crossbow TelosB mote platform. The platform consists of a MSP430 micro-controller and a CC2420 IEEE 802.15.4 compliant RF transceiver operating on the 2.4 GHz frequency band. In [20], it is shown the channel switching time of CC2420 radios takes $300\mu\text{s}$, corresponding to about 19 symbols. The discovery procedures of OPT, SWOPT, and SWEEP were implemented using TinyOS 2.1.1 [21] and the included IEEE 802.15.4 implementation [22].

The setup considered at the experimental evaluation consists of two sensor nodes controlled by a computer. One node periodically transmits beacons, the other performs the discovery according to the respective listening schedule. For each experiment, the channel and the beacon interval are chosen randomly according to a uniform distribution from the channel set C with $|C| = 8$ and beacon order set $B = \{5, 6, 7, 8\}$. After starting the experiment, the scanning node immediately starts processing the discovery schedule, while the neighbor starts transmitting beacons periodically at a time uniformly distributed between $[0; b_T]$. If the scanning node discovers the neighboring node, the experiment is finished and a new experiment is started. The time limit for each run is set to two discovery rounds. Before each experiment repetition, the nodes are reset and accordingly re-configured. The results obtained with each evaluation methods correspond to the average among 1000 repetitions.

5.4 Comparison of the results

The three presented evaluation methods are used to perform a cross validation, according to the parameters shown in Table 7. It is worth mentioning the focus here is on the evaluation of each strategy through different evaluation methods, in order to verify if results obtained in real conditions differ from the simulation and analytical ones. The comparison between the strategies is later presented in Section 6.

Table 6 shows the average discovery time and the 95% confidence intervals obtained through analysis, simulation, and experimentation. Contrarily to SWOPT, PSV and SWEEP, OPT strategy shows slightly higher average discovery time in the experimentation scenario than in the analysis and simulation scenario. Based on the fact that TinyOS is not a real time OS, there is no guarantee that channel switchings occur at the scheduled point in time. Thus, due to the high number of channel switchings imposed by OPT's scanning schedule (i.e., OPT performs 1569 channel switchings per round compared to 58 in SWOPT, 8 in PSV and 32 in SWEEP), the discovery time is increased when OPT strategy is executed in the experimental evaluation. Finally, the results validate the good performance of OPT and SWOPT when applied under realistic conditions.

6 EXTENDED PERFORMANCE EVALUATION

After having cross validated the evaluation methods, this section studies the strategies in a more detailed way, using static and mobile scenarios. This evaluation is done using simulation as described in Section 5.2.

In the next sections, the setup details (cf. Section 6.1) and the performance metrics (cf. Section 6.2) are described. Then,

TABLE 6: Cross validation of evaluation methods using $B = \{5, 6, 7, 8\}$ and $|C| = 8$

Strategy	Simulation		Experimentation		
	Avg. disc. time (s)	Avg. disc. time (s)	Conf. int.	Avg. disc. time (s)	Conf. int.
PSV	14,68	14,71	$\pm 0,18$	14,15	$\pm 0,54$
SWEEP	9,99	9,86	$\pm 0,24$	9,66	$\pm 0,73$
OPT	7,76	7,79	$\pm 0,16$	9,14	$\pm 0,74$
SWOPT	7,39	7,42	$\pm 0,15$	7,36	$\pm 0,46$

TABLE 7: PHY and MAC layer parameters

Carrier frequency	2.40 GHz
Thermal noise	-107 dBm
Transmitter power	1mW
CCA threshold	-77 dBm
Sensitivity	-85 dBm
Symbol duration	16 μs
Time slot duration	15.36 <i>ms</i> (960 symbols)
Channel switching time	19 symbols
MAC beacon payload length	0 bytes
PHY beacon frame length	19 bytes (eq. 38 symbols)
Number of channels $ C $	8
Number of neighbors	16
Beacon order set B	$\{5, 6, 7, 8\}$

the proposed strategies OPT and SWOPT are evaluated in static scenarios regarding parameters related to the assumptions made in the LP model (cf. Section 6.3). The strategy showing the best performance is then compared to PSV and SWEEP strategies, in static (cf. Section 6.4.1) and mobile scenarios (cf. Section 6.4.2).

6.1 Setup details

The parameters shown in Table 7 are considered in the evaluation, if not differently specified. The results correspond to the average among 10,000 runs with 95% confidence intervals. At each run, nodes are assigned to channels and beacon intervals respectively chosen uniformly distributed from the channel set C and beacon order set B . During the simulation, scanning nodes process the discovery schedule given by each strategy, while its neighbors periodically send beacons starting at a time uniformly distributed between $[0; b_I]$. Additionally, when neighbors are not transmitting, we consider that they are in the sleeping state.

We consider static and mobile scenarios:

Static scenario: When not differently stated, the static scenario consists of one scanning node and 16 neighbors placed at uniformly distributed locations in the scanning node’s communication range. Simulation stops when the scanning node discovers all beaconing neighbors or when the time limit for each run reaches two discovery rounds. The latter is required in cases where a beacon will never be received, which may happen due to two or more nodes selecting overlapping beacon transmission times on one channel. Note that this happens rarely and is independent of any discovery strategy’s scheduling.

Mobile scenario: The mobile scenarios consist of one scanning node and 100 neighboring nodes, initially uniformly distributed in a 3000x3000 m^2 area. Nodes move according to the Random Waypoint Mobility (RWM) model, i.e., with constant speeds and pause times randomly selected between

$[0, b_{I_{max}}]$. At each run, the scanning node is performing neighbor discovery during a scan period of about 59 seconds corresponding to one SWEEP discovery round, equivalent to almost two SWOPT/PSV discovery rounds (i.e., almost 63 seconds). To avoid the transient phase of the RWM model the scan is started after 60 simulated seconds.

6.2 Performance metrics

To evaluate discovery speed and reliability, we use the following metrics, according to the type of simulated scenario: (1) *1st discovery time*, which is the time until the first neighbor is discovered; (2) *average discovery time*, which is the average time among the discovered neighbors; (3) *last discovery time*, which is the time when the last neighbor is discovered; (4) *discovery probability*, which describes the percentage of discovered nodes over the total number of neighbors; (5) *average number of discovered and missed (i.e., not-discovered) mobile nodes* among all mobile nodes that sent a beacon while in the communication range of the scanning node and during the considered scan period.

The fast discovery of the 1st node is motivated by emergency applications, where the transmission of a message needs to be performed as soon as possible and consequently, a next hop has to be quickly contacted. A fast average discovery time is interesting (1) in ubiquitous monitoring applications (such as location tracking or in surveillance applications), where neighbors should be identified by a scanning or surveillance entity, and in (2) DTN (Delay Tolerant Networks) scenarios, where nodes need to find a subset of good forwarders. Finally, the fast discovery of the last node is interesting in applications where the discovery of all neighbors of a node is required. In all cases, having a fast discovery will benefit the applications, improving energy efficiency, and allowing quick reaction. Clearly, in mobile scenario, the discovery of all neighbors might not be possible due to the dynamics of the network, but still the proposed discovery strategies could be used to discover the 1st node or a group of nodes (accordingly to some criterion such as a timeout or a minimum number of discovered nodes).

6.3 OPT and SWOPT evaluation

In the following sections, the proposed strategies OPT and SWOPT are evaluated according to the parameters beacon order, beacon length, channel switching time, and beacon loss rate. Thus, we are skipping the assumptions made in the LP model (see Section 4.1.2) and evaluating the strategies under more realistic conditions. The evaluation includes simulation (i.e., “sim.”) and analytical (i.e., “ana.”) results.

6.3.1 Impact of beacon order

We show in Figure 2(a) the comparison between the first, average, and last time required to discover nodes with different beacon orders. Parameters of Table 7 are considered with beacon order set $B = \{5, 6, 7, 8, 9, 10\}$. The first discovery time of the strategies is almost identical. However, for the average and last discovery time the SWOPT strategy shows lower discovery times. The analytical and simulation results regarding the average discovery times are almost identical.

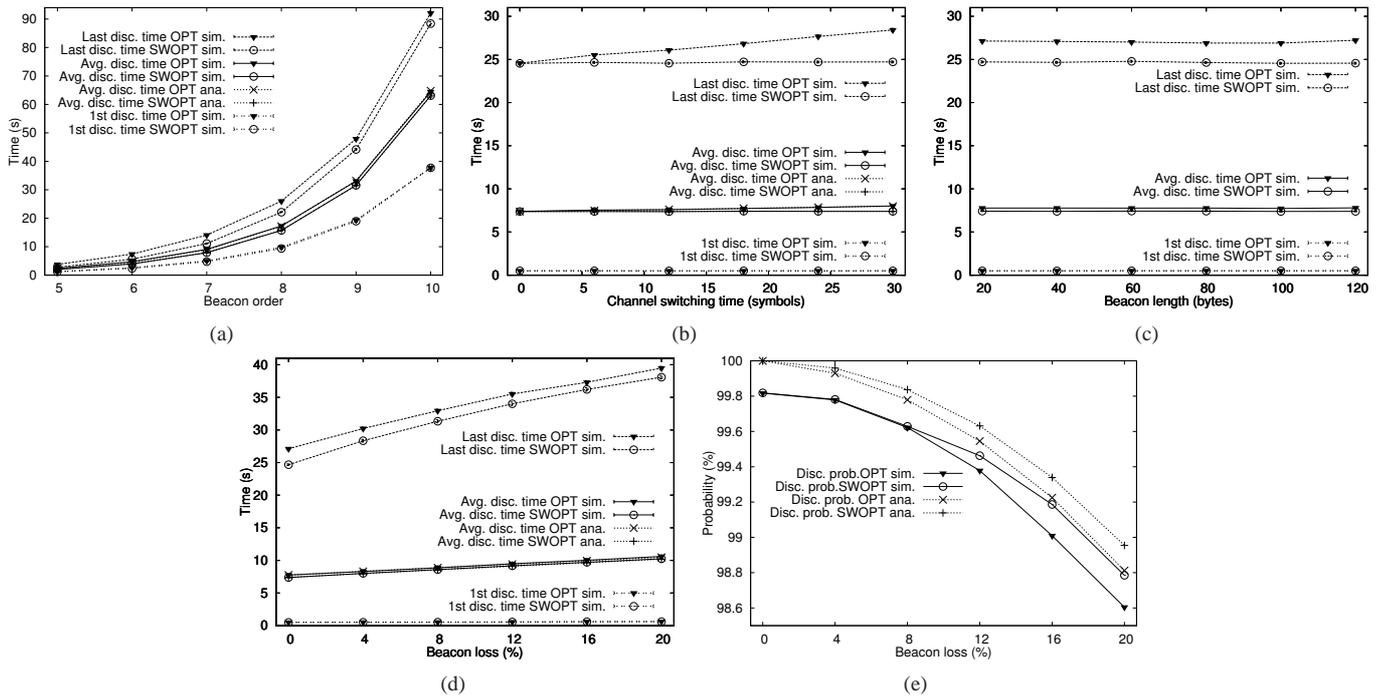


Fig. 2: OPT and SWOPT evaluation for varying (a) beacon orders, (b) channel switching times, (c) beacon lengths and (d)-(e) beacon loss rates

6.3.2 Impact of channel switching time

Figure 2(b) depicts the impact of the channel switching time on the discovery time, when considering parameters of Table 7. Again both strategies have about the same first discovery time which is constant with increasing channel switching time. There is also no visible impact on the average and last discovery time of the SWOPT strategy. However, the OPT strategy shows an increasing average and last discovery time for higher channel switching time. This is caused by the high number of channel switchings required by the OPT strategy: in this scenario, OPT performs 1569 switches per round compared to 58 in SWOPT.

6.3.3 Impact of beacon length

Figure 2(c) shows the first, average, and last discovery time results for beacons with a PHY frame lengths varying from 20 to 120 bytes (resulting in about 0.04 to 0.25 ratio of beacon transmission duration to time slot duration) and for parameters listed in Table 7. No impact is perceived to the performance of the strategies. In particular, as discussed in Section 4.3.3, if a beacon is received shortly before the switching to another channel is scheduled, the listening time on the next channel is delayed and shortened by the delay caused by the beacon reception. Thus, in order to impact the discovery time, a beacon has to be received on a channel before the listening of a scanning node starts on this channel. The probability for such event happening is very low. SWOPT presents better average and last discovery time results than OPT. This is caused by the non-zero value used for channel switching time, i.e., 19 symbols (see Table 7).

6.3.4 Impact of beacon loss

Figure 2(d) depicts the impact of beacon loss on the discovery time. The first discovery time is identical for both strategies and almost constant with an increasing beacon loss rate. The average and last discovery time show to be impacted by the beacon loss: as expected, a higher impact is, however, observed for the last discovery. The analytical results for average discovery time match the simulation results. Finally, the SWOPT strategy shows better results for the average and last discovery time than the OPT strategy.

The discovery probability as a function of the beacon loss rate is plotted in Figure 2(e). Two discovery rounds were performed. The SWOPT strategy shows a lower impact on the discovery probability than OPT. This is due to its lower number of channel switching compared to the OPT strategy: in presence of losses, the chances of missing a node at the discovery while performing a channel switching is higher. There is a discrepancy between the simulation and analytical results. This is caused by the definition of the beacon loss parameter. In the simulation the beacon loss rate is computed on the receiver node after having correctly received a beacon. However, simulation also considers beacons with a non-zero frame length causing a possibility for beacon collisions if multiple nodes select the same operating channel and time. Therefore, even with zero beacon losses the discovery probability for the simulation results is not 100%. Beacon length is not considered in the analysis, which explains the differences in performance.

6.4 PSV and SWEEP comparison

The last section has shown that the SWOPT strategy outmatches in performance the OPT strategy. Thus, in this section,

we will compare SWOPT with the multi-channel passive discovery strategies PSV and SWEEP. The performance of the strategies is studied in static and mobile scenarios using simulation with varying parameters.

6.4.1 Static scenario

6.4.1.1 Impact on beacon order: We show in Figure 3(a) the comparison between the first, average, and last time required to discover nodes with different beacon intervals (i.e., for $B = \{5, 6, 7, 8, 9, 10\}$), according to the SWEEP, PSV and SWOPT discovery strategies. Results show how the SWOPT and SWEEP strategies accelerate those discovery times when compared to the PSV strategy. Compared to PSV, the SWEEP strategy shows better results to all beacon orders except for $b_{max} = 10$, where all the analyzed discovery times are higher than the ones resulted from PSV. However, SWOPT shows better result to all beacon orders compared to both other strategies. Moreover, note that SWOPT do not add any additional delay to the discovery of the highest beacon order b_{max} when compared to the results given by the PSV strategy. It results in the same first, average, and last discovery time as PSV strategy. This also validates the intuition behind the LP model: to accelerate the neighbor discovery for the smaller beacon intervals of set B , at each channel $c \in C$.

6.4.1.2 Impact of channel switching time: Figure 3(b) proves how the approach for channel switching time described in Section 4.3.2 combined with the three strategies is able to reduce the impact on the schedule. The first, average, and last discovery times are constant for increasing channel switching time. SWOPT presents the shortest discovery times with an average discovery time half as much as PSV. The first and average discovery time of SWEEP is lower than the times of the PSV strategy, but for the last discovery time PSV shows better results.

6.4.1.3 Impact of beacon length: Figure 3(c) shows the discovery times results for beacons with a PHY frame lengths varying from 20 to 120 bytes (resulting in about 0.04 to 0.25 ratio of beacon transmission duration to time slot duration), for the three strategies. No impact is perceived to the performance of the strategies. The results are similar to the evaluation of the channel switching time in Figure 3(b). SWOPT shows the lowest first, average and last discovery time, while SWEEP has lower first and average discovery time than PSV, but higher last discovery time.

6.4.1.4 Impact of beacon loss: Figure 3(d) depicts the discovery times as a function of the beacon loss rate. All strategies show an increase in the average and last discovery time if the beacon loss rate is increased. The first discovery time is nearly constant. The slope of the SWEEP discovery time is higher compared to the curves to the PSV and SWOPT strategies. Again SWOPT shows the lowest discovery times.

Figure 3(e) shows the discovery probability subject to the beacon loss rate. In the static scenario the simulation time limit was set to two discovery rounds. Using $|C| = 8$ and $B = \{5, 6, 7, 8\}$, one SWEEP discovery round consists of 3840 time slots compared to 2048 time slots used in one round of the PSV or SWOPT strategy. Therefore the total listening time of SWEEP is almost twice as much as of the other strategies, which helps mitigating the impact of the beacon loss.

TABLE 8: First and average discovery time for varying duty cycles

Duty cycle	1st disc. time			Avg. disc. time		
	SWEEP	PSV	SWOPT	SWEEP	PSV	SWOPT
$\approx 1.6\%$	10,59	55,15	19,37	620,60	940,95	464,90
$\approx 3.1\%$	1,74	22,69	5,32	299,26	471,00	227,20
$\approx 6.3\%$	0,50	10,56	0,96	138,59	238,76	109,50
12.5%	0,49	5,16	0,49	64,44	124,55	51,08
25.0%	0,49	1,33	0,50	29,74	61,82	23,10
50.0%	0,49	1,02	0,49	14,59	30,42	11,33

6.4.1.5 Impact of number of channels: Figure 4(a) shows how much faster the SWOPT strategy allows neighbor discovery for increasing number of channels compared to SWEEP and PSV strategies. Although all the strategies present a linear increasing discovery time, the PSV strategy results in much higher increases of the first and average discovery time for higher number of channels. For the last discovery time, the increase of the SWEEP strategy is the highest. It is interesting to note the almost stable behavior of SWOPT and SWEEP for the 1st discovery time, for increasing number of channels.

6.4.1.6 Impact of beacon order set: Figure 4(b) and Figure 4(c) evaluate respectively, the average discovery time of the strategies under different (1) numerical distances between the minimum and maximum beacon order, i.e. for $(b_{max} - b_{min})$ equals to 1 and 5 and (2) sizes of beacon order set, i.e. for $|B|$ equals to 2 and 6.

It is worth noting that for higher values of $(b_{max} - b_{min})$, SWOPT performs better than SWEEP and PSV. Additionally, big sizes of beacon order sets are also beneficial to SWOPT strategy. This is due to the optimization, which speeds up the discovery of nodes with low beacon orders per channel.

6.4.1.7 Impact of number of nodes: Figure 4(d) shows the impact of the network density on the discovery time of the strategies. The number of nodes in the communication range of the scanning node is varied from 1 to 30. In all the strategies, the increase on the nodes density does not impact the average discovery time. This is because of the randomly uniform selection of the operating channel and of the beacon starting time (i.e., between $[0; b_I]$). Nevertheless, as expected, the time to perform the 1st neighbor discovery decreases with the density and the last discovery time increases.

Finally, as already shown in other scenarios the average discovery time of SWOPT is lower than the one of SWEEP and about half of the average discovery time of PSV. With increasing node density the first discovery time of the strategies become almost identical. Also the last discovery time of SWOPT advances towards the PSV last discovery time. The last discovery time of SWEEP is again the highest.

6.4.1.8 Impact of duty cycle: One known problem in neighbor discovery is that discovery latency is inversely related to energy consumption: Low duty-cycling of scanning nodes results in low energy consumption but higher discovery latencies. This section evaluates the impact of increasing scanning node's duty cycles (DC) on the discovery time of the three strategies. For this, in Table 8, we vary the active period of the scanning node in each discovery round by each strategy. Thus, if DC is 25%, the scanning node will be active only 25% of one round and consequently, will only process 25% of the

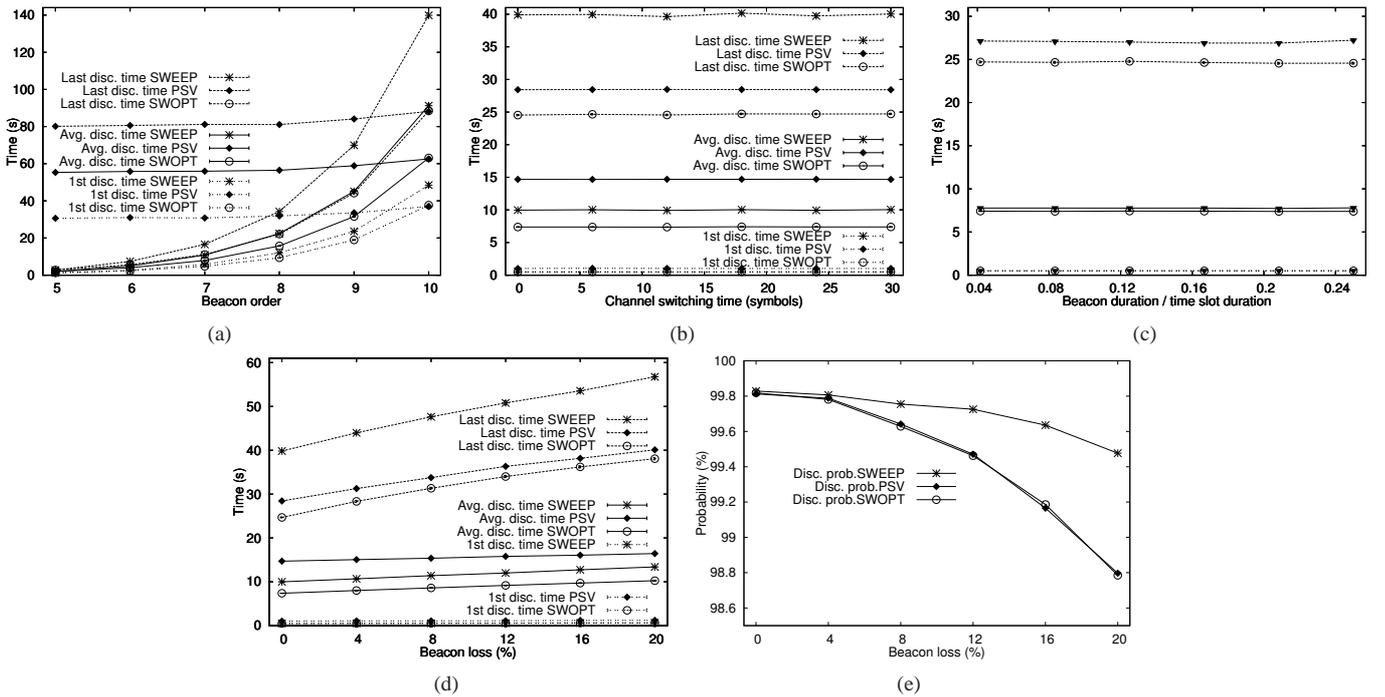


Fig. 3: SWOPT, SWEEP, and PSV evaluation in a static scenario for varying (a) beacon orders, (b) channel switching times, (c) beacon lengths and (d-e) beacon loss rates

discovery schedule per round. This results in lower energy consumption per round, but increases the number of rounds required to perform the whole schedule. Note that even if the strategies have the same DC, the active number of slots per round of the SWEEP strategy is higher than PSV and SWOPT, due to its higher total number of slots per discovery round.

As expected, as shown in Table 8, higher is the scanning node's DC, faster is the discovery performed by all the approaches. Due to its higher number of active slots per discovery round, the first discovery time of the SWEEP strategy is lower than SWOPT for lower duty cycles. For the average discovery time SWOPT provides the lowest discovery time even when using less number of scanning time slots. This confirms that besides supporting discovery in multi-channel and different beacon intervals conditions, SWOPT strategy can also provide fast and good discovery reliability in situations with low duty-cycling scanning nodes.

6.4.2 Mobile scenario

Figure 4(e) shows the 1st and average discovery time for varying nodes speed. Results show that the SWOPT strategy achieves faster first and average discovery when compared to PSV and SWEEP. In all the strategies, the time for performing the first discovery decreases with the increase of nodes speed. In fact, the increase in nodes speed increases the number of neighbors visiting the scanning node's range during the scan period, this also increases the probability of finding at least one node in a short period of time. The average discovery time of all strategies also decreases in higher speeds: At higher speed, the ratio of discovered neighbors with lower beacon order increases over the total number of discovered nodes.

Figure 4(f) shows the average number of discovered and

missed nodes as a function of the nodes speed. For speeds of 5 m/s all strategies discover and miss almost the same number of nodes in average. With increasing speeds the SWOPT strategy discovers more nodes and miss less nodes in average. At higher speeds the average number of missed nodes even exceeds the average number of discovered nodes for the PSV and SWEEP strategies.

7 LOW COMPLEXITY IMPLEMENTATION

As shown in the previous sections, the SWOPT strategy provides an optimized listening schedule regarding the average discovery time, which results from a LP optimization. For a given channel set C and beacon order set B , this optimization can be computed offline but requires a lot of computational power. In addition, the computed schedule has to be completely stored in the memory of a device. Therefore, a low-complexity algorithm requiring less memory usage and allowing local computation on a node is desirable, even if the provided listening schedule results in a (sub-)optimal solution. This section presents our answer for this requirement.

7.1 Sub-optimal algorithm

We propose the use of the low-complexity algorithm shown in Algorithm 1, named SUBOPT. Nodes executing the listening schedule given by SUBOPT listens for $b_{I_{min}}$ ($= 2^{b_{min}} \cdot z$) number of slots successively on all channels of set C starting at channel 0 to c_{max} . This is repeated for a number of iteration which can be computed by $iter = \frac{b_{I_{max}}}{b_{I_{min}}}$. Due to the structure of the beacon interval, $b_{I_{max}}$ is always a multiple of $b_{I_{min}}$ resulting in $iter$ to be an integer.

If the number of channels $|C|$ is odd, the SUBOPT algorithm will yield in a listening schedule that gives the same

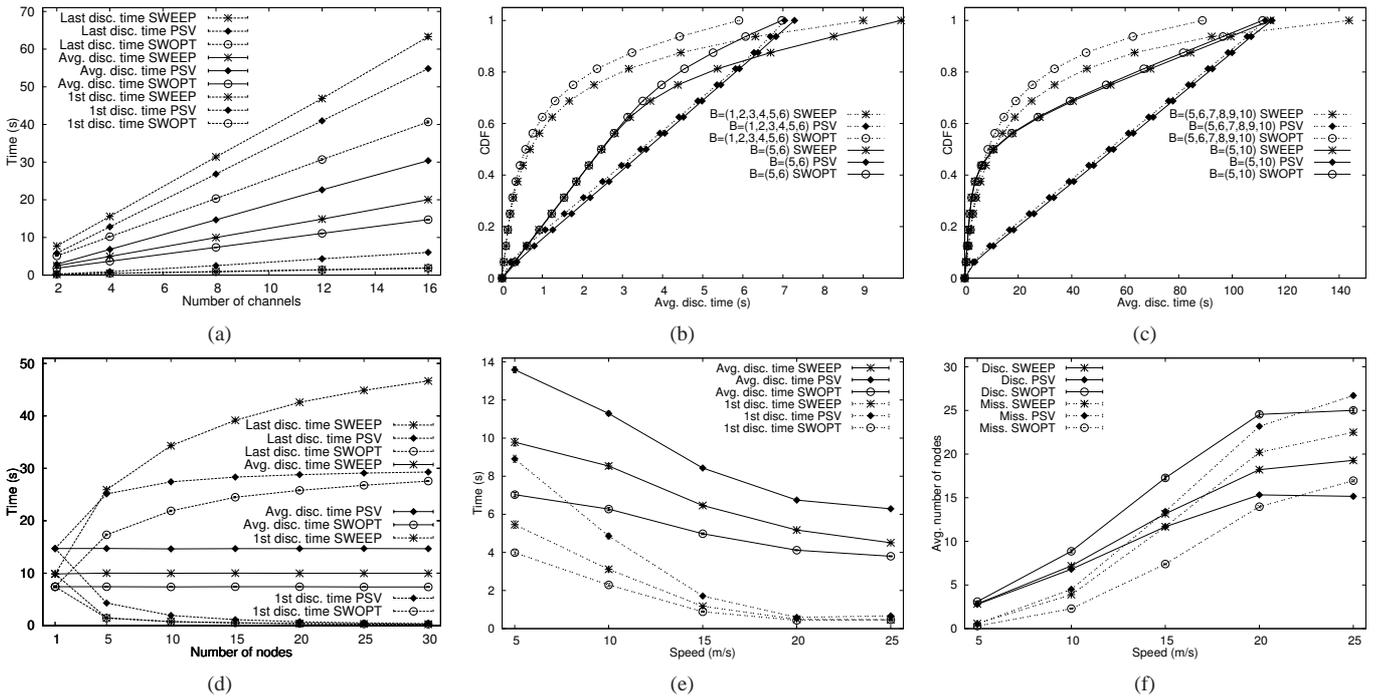


Fig. 4: SWOPT, SWEEP, and PSV evaluation: (a)-(d) In static scenario for varying (a) number of channels, (b)-(c) beacon order sets, and (d) number of nodes. (e)-(f) In a mobile scenario for varying speed

result as SWOPT, regarding the optimization goal, but with much lower complexity overhead. Nevertheless, that basic listening strategy is not applicable if the number of channels $|C|$ is even. A simple counterexample is $|C| = 2$ and $B = \{0, 1\}$. If the described approach is applied, all time slots scanned on channel 0 are even and on channel 1 odd. Even if repeated multiple times only half of all nodes operating with $b = 1$ will be discovered. No low-complexity general pattern resulting in an optimal listening schedule could be found for the case where the number of channels $|C|$ is even.

As a countermeasure, we propose to add an additional sleeping period with the length of $b_{I_{min}}$ at the end of each iteration, in scenarios with even number of channels. In this case, SUBOPT pretends to have $|C| + 1$ channels. Thus, a discovery round for a given beacon order set B and channel set C will require more time slots than the related SWOPT strategy. The discovery time of the SUBOPT strategy will be increased compared to SWOPT. The increase depends on the difference between $b_{I_{min}}$ and $b_{I_{max}}$. If $b_{I_{max}}$ is much larger than $b_{I_{min}}$, the additional sleeping periods will have only a minor impact on the discovery time. On the other hand, if $b_{I_{max}}$ is very close to $b_{I_{min}}$, the sleeping periods take up a large part of the discovery schedule.

7.2 Performance evaluation and comparison

We evaluate the SUBOPT algorithm through analysis, experimentation, and simulation and compare it to the SWOPT strategy. For this, two different static scenarios with odd and even number of channels are used. The same setup described in Section 5 is considered and results are shown in Table 9. In case of odd number of channels ($|C| = 7$),

Algorithm 1 Pseudocode of the suboptimal algorithm (SUBOPT)

```

iter :=  $\frac{b_{I_{max}}}{b_{I_{min}}}$ ;
t := 0;
for i := 1 to iter do
  for j := 0 to  $c_{max}$  do
    for k := 1 to  $b_{I_{min}}$  do
       $c_t := j$ ;
      t := t + 1;
    end for
  end for
  if  $|C| \bmod 2 = 0$  then
    for k := 1 to  $b_{I_{min}}$  do
       $c_t := sleep$ ;
      t := t + 1;
    end for
  end if
end for

```

SUBOPT and SWOPT result in the same average discovery time with consideration of the confidence interval. On the other hand, in the scenario with $|C| = 8$, SUBOPT results in an increased average discovery time caused by the additional sleeping periods. Although such time increasing, SUBOPT still performs better than PSV and SWEEP, when the results shown in Table 9 are compared to the ones shown in Table 6.

8 DISCUSSION AND OUTLOOK

This paper presents practical and optimized solutions for the asynchronous and passive multi-channel neighbor discovery problem, enabling efficient usage of heterogeneous hardware platforms (i.e., network environment composed by nodes operating with different beacon intervals). Our optimized solutions

TABLE 9: SUBOPT and SWOPT evaluation

(a) $ C = 7, B = \{5, 6, 7, 8\}$						
Strategy	Analysis		Simulation		Experimentation	
	Avg. disc. time (s)	Avg. disc. time (s)	Conf. int.	Avg. disc. time (s)	Conf. int.	
SUBOPT	6,47	6,46	$\pm 0,03$	6,47	$\pm 0,40$	
SWOPT	6,47	6,48	$\pm 0,03$	6,19	$\pm 0,42$	

(b) $ C = 8, B = \{5, 6, 7, 8\}$						
Strategy	Analysis		Simulation		Experimentation	
	Avg. disc. time (s)	Avg. disc. time (s)	Conf. int.	Avg. disc. time (s)	Conf. int.	
SUBOPT	8,07	8,06	$\pm 0,04$	8,05	$\pm 0,59$	
SWOPT	7,39	7,42	$\pm 0,15$	7,36	$\pm 0,46$	

are based on linear programming (LP) optimization and result in the discovery strategies named OPT and SWOPT. Additionally, we propose a practical solution named SUBOPT that relies on the proposal of a low-complexity algorithm requiring lower memory usage. We do not impose any constraints on the transmission of the beacons and depend only on their periodicity with unknown period belonging to a set of permitted values. We have shown through analytical, experimental, and simulation results that the OPT, SWOPT, and SUBOPT strategies allow major part of neighbors being discovered faster (except for nodes operating with the maximum beacon order b_{max}) than the passive discovery of IEEE 802.15.4 standard and of SWEEP.

In particular, such results were also obtained when considering simulated static scenarios with varying network settings. In mobile scenarios, the SWOPT strategy allows higher discovery ratio, besides of faster discoveries. We believe that emergent heterogeneous static and mobile wireless applications (like docking, tracking, or infrastructure monitoring applications) require a continuous, asynchronous, multi-channel neighbor discovery process. Our strategies allow getting such discovery in a practical and efficient way.

Looking forward, we envision several directions for extending work. One direction would be to provide scheduling solutions to discover any kind of beacon interval. One obvious extension would be adding gossip support to the strategies. The idea consists in allowing neighbors speeding up neighbor discovery of scanning nodes, by gossiping about the neighbors they have already discovered when in their scanning state. Extending the ideas presented in this paper to support opportunistic-based discovery could also be fruitful and timely. The idea is to use overhearing of any transmission (data or beacon) to speed up the discovery.

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