

Research Article

Opportunistic Data Collection in Sparse Wireless Sensor Networks

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Opportunistic wireless sensor networks (WSNs) have recently been proposed as solutions for many remote monitoring problems. Many such problems, including environmental monitoring, involve large deployment scenarios with lower-than-average node density, as well as a long time scale and limited budgets. Traditional approaches designed for conventional situations, and thus not optimized for these scenarios, entail unnecessary complexity and larger costs. This paper discusses the issues related with the design and test of opportunistic architectures, and presents one possible solution—CHARON (Convergent Hybrid-replication Approach to Routing in Opportunistic Networks). Both algorithm-specific and comparative simulation results are presented, as well as real-world tests using a reference implementation. A comprehensive experimental setup was also used to seek a full characterization of the devised opportunistic approach including the derivation of a simple analytical model that is able to accurately predict the opportunistic message delivery performance in the used test bed.

1. Introduction

Advances in miniaturized electronic systems and wireless communications have enabled their use for monitoring applications in scenarios which were previously very difficult or even impossible to monitor, giving birth to the field of wireless sensor networks (WSNs). These networks comprise a potentially large number of small nodes of limited capacity, communicating with each other using wireless links, also of limited range [1].

Many of the applications envisioned for WSNs, such as agricultural and habitat monitoring, require spreading the network over relatively large areas, causing the radio range to be insufficient to assure a fully and permanently connected network. The network will, therefore, be split into several partitions that are unable to directly transfer information to each other. For some networks, this is not a problem, as there can be individual base stations (sink nodes) that receive

and use the information from their respective partitions. For others, however, such sink deployment may be impossible or impractical, or full connectivity may be an important application requirement.

In such cases, node mobility emerges as a possible solution. By making some nodes mobile and exploiting their mobility, new communication opportunities are created among otherwise isolated network elements. In some applications, such as wildlife monitoring, mobility may even be part of the problem specification, so taking advantage of it seems a logical choice. But exploiting node mobility comes with a price: data exchanges only take place intermittently, when nodes are in range. This is what is typically known as opportunistic communication [2]. Opportunistic communications are intrinsically challenging to several network layers, and applying these principles to WSNs presents additional problems and specificities which must be carefully considered. The primary concern is, of

course, the chronic lack of resources, including storage space, execution memory, processing, and transmission power. The most serious limitation, though, is that of energy supply, as most nodes run on batteries with a finite and relatively short lifetime, after which human intervention is required to keep the network running. Energy harvesting techniques can alleviate this problem, but generally they are not sufficient to sustain large power consumption situations without the help of software-assisted power management solutions [3].

The most significant challenge in opportunistic WSNs is, generally speaking, routing. Traditional algorithms are not applicable, as they assume the existence of end-to-end routes. In an opportunistic network, the topology becomes extremely volatile, and complete end-to-end routes may never exist at any single point in time—a situation falling within the realm of disruption and delay-tolerant networks (DTNs). Furthermore, there are always application-specific requirements and constraints, and it is close to impossible to design a good general-purpose algorithm. Of the existing protocols, many assume resources or behaviours which are not entirely compatible with the characteristics of most WSNs and the requirements of the applications they support. They suffer from the all-too-common problem of having been designed for the simulator instead of the real world [4].

As there are very different opportunistic WSN scenarios, it is very hard, if not impossible, to develop a true general-purpose solution. To come up with a realistic solution, we began narrowing our focus by specifying a sensible set of restrictions and related architectural constraints. Sparse networks, those with low node density, are the most interesting, as they cannot make use of traditional adhoc routing algorithms, and the most challenging, since decisions carry a graver impact on global performance. We also assume networks to be highly scattered, thus negating the need for hybrid routing protocols, which include a separate, nonopportunistic mechanism for routing inside permanently-connected partitions. We focus on highly mobile networks, in which the majority of nodes (or all of them) move, as mostly static networks are easily served by a MULE-like architecture [5]. Realistically, there are few situations in which it makes sense to have on-demand mobile agents, so we assume passive mobility with stochastic evolution. That does not imply, however, the total absence of movement patterns on the network. Consequences of high-speed movement, found in scenarios such as motorways and railway networks, are outside the scope of our work. Resource constraints are also taken into account, especially processing speed, memory capacity and energy. Finally, in most (but not all) sensor networks, the goal is to collect data from sensors and deliver it to a central node (sink) for analysis. This is best accomplished by using what is commonly known as a *convergecast* architecture. Additionally, an *any-sink* property is assumed, meaning that several sinks may exist, and delivery to any one of them is sufficient.

In short, we will be focusing on low-density, highly mobile data collection networks with stochastic evolution, possibly using multiple sinks. Nodes are assumed to be resource-constrained, particularly in relation to energy. This is a reasonable set of assumptions and the resulting scenario

is commonly found in real-world applications including environmental, wildlife and silvopastoral systems monitoring. This paper proposes a solution that can be used to effectively and efficiently route messages in that scenario, without compromising its simplicity and, consequently, its feasibility. The proposed approach is named CHARON—Convergent Hybrid-replication Approach to Routing in Opportunistic Networks [6]. It uses an history-based collection algorithm, with delay as the main routing metric and aims to minimize the number of message exchanges, while still providing a way for urgent messages to be delivered quickly. It also features integrated time synchronization and radio power management, features seldom found but of critical importance to achieve good energy efficiency. In [6] an overview of CHARON, emphasizing its routing component and corresponding preliminary evaluation, was presented. Here, we provide a more exhaustive discussion on CHARON's design and evaluation, introduce a detailed description of the additional features and present a comprehensive experimental characterization of this opportunistic architecture, including the derivation of a simple analytical model that is able to accurately predict the opportunistic message delivery performance in a real-world test bed.

The remainder of this paper is organized as follows: in Section 2, we briefly go over some of the related work; in Section 3, our solution and its features are described in detail; in Section 4, we present both CHARON-specific and comparative simulation results; in Section 5, we evaluate the performance of the additional (nonsrouting) features; in Section 6, we present an extensive experimental characterization, involving both real-world experiments and theoretical modelling; finally, in Section 7, we wrap up with some conclusions and future work.

2. Related Work

In this section, we will briefly review some currently available opportunistic routing solutions. While there are many more, most of them have very limited applicability to the target scenario. All of the discussed approaches are either probabilistic or history based, which, in addition to being the most common, generally present a good balance between complexity and practicability.

2.1. Epidemic Routing. Epidemic routing [7], one of the first proposed opportunistic routing algorithms, was modelled from the manner in which diseases spread in the population. When two nodes are in range they trade summary vectors containing the unique identifiers of the stored messages and use them to determine which messages to transfer. The vectors contain both currently and previously carried messages, preventing a node from receiving the same message twice. Epidemic Routing is in effect a pure flooding algorithm, with each node diffusing messages to all of its neighbours. This, in turn, means that it requires very little information about the network, which makes it useful for a wide range of scenarios. Its main weaknesses are the heavy use of storage space and radio transmissions.

2.2. Spray and Wait. Spray and wait [8] attempts to reduce duplication by limiting the maximum number of copies of a single message. It works in two separate phases as the name suggests: the spray phase and the wait phase. During the spray phase, messages are spread over the network, up to an established limit on the number of copies. Afterwards, during the wait phase, nodes keep the messages stored until they come within reach of the destination node, in which case they deliver it. During the wait phase there is no additional forwarding or duplication of messages.

2.3. Data MULEs. The authors of Data MULEs [5] propose a three-tier architecture (composed of sensors, mobile agents, and access points) designed for sparse networks. Mobile agents, named MULEs (Mobile Ubiquitous LAN Extensions) randomly move around, picking up data from sensors when in close range and dropping it at access points, connecting otherwise partitioned networks while lowering transmission range and energy requirements. As MULEs have more resources (energy, storage, etc.) than sensors, most of the routing effort is moved to them, further reducing CPU energy consumption on the nodes.

2.4. ZebraNet. ZebraNet [3, 9] was a pioneering project in wildlife monitoring using WSNs, intended to allow tracking of individual wild zebras' positions under strict constraints, the most notable of which is the absence of fixed infrastructure. It uses self-sufficient tracking collars carried by the zebras, and a vehicle-mounted base station that periodically moves around the territory. The network features node-to-node and node-to-sink communications and uses one of two routing protocols: either a pure flooding variant or a history-based protocol. The history-based protocol forwards the data to the nearby node with the highest hierarchy level, a simple integer counter that is periodically increased if the node is in range of the sink or decreased otherwise.

2.5. PROPHET. The Probabilistic ROuting Protocol using History of Encounters and Transitivity (PROPHET) [10] uses delivery probability information to choose the best forwarding path. When two nodes meet, they exchange both a summary vector and a delivery probability vector, containing the delivery probability to each known node. The delivery probability metric is derived from previous encounters and subject to an ageing factor. It has a transitive property that allows calculation of probabilities to destinations which the node has never had direct contact with. Following the vector exchange, messages are transferred from the lower to the higher delivery probability node, but they are not deleted from the source node as long as there is available buffer space, allowing for the possibility that in the future the node may find a better forwarder or even the destination.

2.6. SCAR. Sensor Context-Aware Routing (SCAR) [11] is loosely based on a previous protocol, CAR [12], but it was specifically thought for use in WSNs. In particular, they share the same prediction model, using Kalman filters, but the communication and replication aspects were redesigned

considering the resource limitations and high fault rate of WSNs. The combined delivery probability is forecast from sink collocation, sensor connectivity change rate (a measure of relative mobility) and battery level. Source nodes keep an ordered list of neighbouring nodes and replicate each message to the top R (the application-specific replication factor, which can also be thought of as a priority level). The message copy delivered to the first sensor is known as the master copy, while the rest are secondary copies. From then on, nodes forward messages when they encounter a better carrier, but do not replicate them, thereby limiting the number of message copies. While master copies are only deleted on delivery to a sink, secondary copies can also be erased if buffers are full.

2.7. Discussion. Few of these approaches have withstood real world testing, and most have never even been implemented outside the simulation environment used by the authors. The most used are probably the epidemic routing algorithm [7] and the ZebraNet history-based algorithm [9], which are also two of the simplest. This should come as no surprise given that, by expanding the underlying assumptions, many algorithms are implicitly restricting their applicability, either because of hardware limitations, lack of required information or plain inadequacy to the network structure, requirements or movement patterns. Some algorithms do this in accordance with the longstanding trend in WSNs (or, to be precise, in any heavily constrained system) of using scenario-specific solutions as a way to optimize performance. Others go the opposite direction, aiming for such generality that they risk becoming too complex for any real scenario.

3. CHARON Design

We intend for CHARON to be a complete though minimalist end-to-end solution for opportunistic WSNs, although its main component is the most critical in this setting: the routing algorithm. Ideally, a user wanting to deploy an application would just have to develop the sensing logic for the nodes, dispatch the messages to CHARON, and then handle data processing at the base station, ignoring everything else. Nevertheless, this model is not suitable to all applications and, with flexibility as one of our main goals, we do not limit the user in any way.

CHARON's routing component is a history-based routing algorithm. It shares the same basic operating principle as other algorithms in that class: nodes exchange and/or record some kind of historic information when they meet and make routing decisions based on that information. The main historic routing metric used in CHARON is delay, as previously proposed in other contexts [13]. The expected delivery delay through each node (its Estimated Delivery Delay or EDD) is determined, and messages are routed along a decreasing delay gradient having a sink node as its end. We decided to use this metric, versus, for instance, the nodes' relative mobility or sink encounter frequency, in an effort to align the mechanism to the goal, which is to get the data to the sinks before it expires.

```

// For a contacted node c
algorithm forward_if_better(c) is
    if score(c) ≥ score(self) and EDD(c) < EDD(self) then
        forward_messages(c)
    end
end

```

ALGORITHM 1: Forwarding decision algorithm.

Nonetheless, optimizing delay is not the only concern, as limited network resources must also be considered in order to provide a truly efficient solution. To accommodate that requirement, while also providing easy customizability, a multivariate utility function is used to compute an additional score for each node. The utility function is of optional character: if undefined, routing is based solely on minimizing the delay. If it is defined, it can use the CHARON-provided free buffer space and available energy data, and/or draw on other application- or system-provided metrics.

Decisions are made based on both the nodes' EDDs and the values assigned to each by the utility function, if defined. Messages are forwarded if the other node's EDD is lower than the node's own, and if the score is the same or higher (Algorithm 1).

Messages are forwarded using a basically single-copy approach, meaning that there is only one regular copy of a message in the network at any single time. Nonetheless, there is always implicit message copying, as every time a message is forwarded a copy is left behind. Instead of deleting messages on transmission, CHARON retains them in a special state that does not allow further forwarding, except in the case that the node meets a sink. Messages in this state are known as *zombies*, and we refer to the strategy as *hybrid replication*. The traditional multicopy paradigm is also supported for situations that require it.

In order to realize the intrascenario flexibility objective, basic Quality of Service (QoS) mechanisms were designed into the solution. QoS classes may be configured, and each can use a different replication strategy and utility function. This allows CHARON to provide very reliable (though inefficient) service to urgent or important messages, whilst maintaining high efficiency for the majority of (delay and disruption tolerant) messages.

As minimizing the number of transmissions is not enough to provide an energy-efficient solution, CHARON has built-in support for synchronous radio power management, significantly reducing energy waste. As a global time reference is not always available, a very simple and low-precision synchronization mechanism was integrated, making use of just two values: the node's existing reference and its age.

CHARON operates as a bundle layer, being implemented atop a network stack provided with the platform. By relying on already available lower-level protocols and avoiding duplicated functionality, this approach manages to significantly reduce the size and complexity of CHARON's

implementation. There is a small impact on communication efficiency, leading to longer frames due to extra encapsulation—a generally advantageous tradeoff. Furthermore, it helps make the solution platform-agnostic and independent of the low-level details. There are only two types of messages in CHARON: beacons, which relay routing information, and bundles, which carry application data. Throughout this paper, the terms message and bundle are used interchangeably.

Each specific features of CHARON will be discussed in detail over the following subsections.

3.1. Routing Metric. The basic idea of our delay-based algorithm is to route messages in such a way that their expected delivery delay decreases with each hop. To do so, the expected delivery delay of each node must be estimated, considering its movement patterns. Two parameters are defined.

- (i) Estimated Delivery Delay (EDD) is a characteristic of each node and describes the estimated time a message delivered to that node will take to reach a sink. Sink nodes have an EDD of 0.
- (ii) Inter contact Time (ICT) is a characteristic of each node pair (or link) and is a measure of the expected time between encounters of those two nodes. The ICT is not defined (or can be thought of as infinite) for a pair of nodes that never met.

A node ($v \in V$) maintains a list of its contacts ($V_v \subseteq V$) and records the advertised EDD for each contacted node. It also computes the ICT, through an exponentially weighted moving average (EWMA) of the intervals between previous encounters. From node v 's perspective, the perceived delay (d) through a known contact (c) is given by the sum of its EDD ($\text{edd} : V_c \rightarrow \mathcal{R}^+$) and the ICT ($\text{ict} : V, V_v \rightarrow \mathcal{R}^+$) between both nodes.

$$d(v, c) = \text{edd}(c) + \text{ict}(v, c), \quad c \in V_v. \quad (1)$$

In fact, ICT is a measure of the expected worst case encounter delay so, for the average delay, its half should be considered. Yet, both strategies are equivalent as long as there is coherence, and this way the number of required arithmetic operations is slightly reduced.

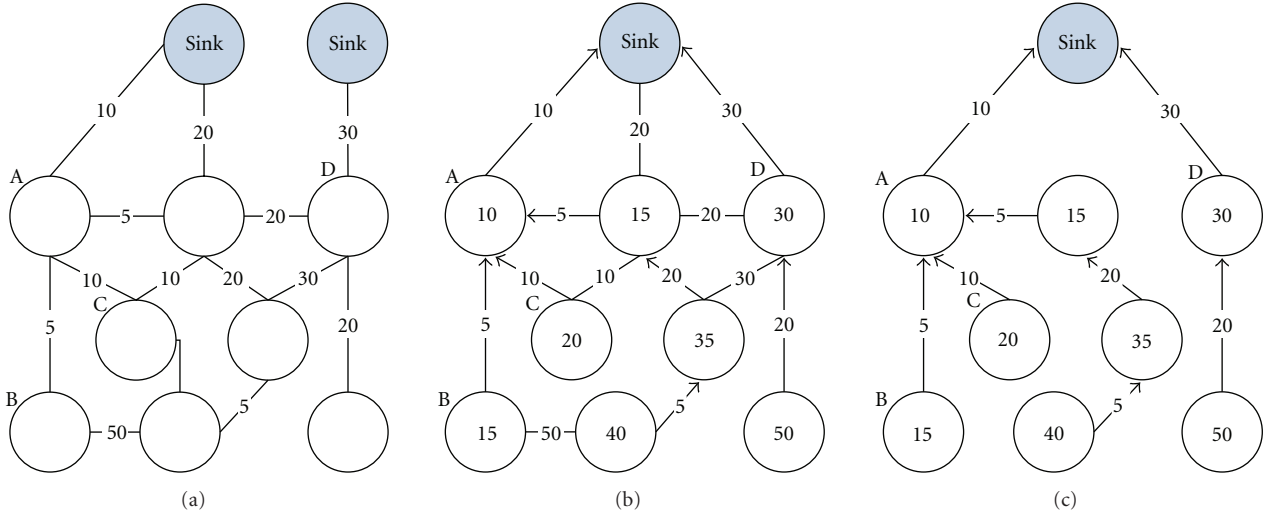


FIGURE 1: Steps of EDD calculation from ICT values.

A node's EDD is equal to the minimum achievable delay, or the delay through the quickest known node, given by.

$$\text{edd}(v) = \min_{c \in V_v} \{d(v, c)\}. \quad (2)$$

In practice, this means CHARON uses a transitive delay metric with an additive concatenation operator and an extra variable per-hop factor. As a consequence, EDD is only defined for nodes with a complete chain of contacts ending in a sink. It is easier to visualize this by representing the network as a graph, seen in Figure 1. Graph nodes correspond to network nodes, and are marked with their EDD, while edges correspond to "known node" relationships and are marked with the recorded ICT. A node's EDD is given by its shortest path weight to the virtual sink, representing all real sinks.

A problem with this approach is that ICTs do not degrade naturally, that is, if two nodes ($a, b \subset V$) do not meet, their ICT value stays unchanged. This may have serious consequences if b is a 's best known forwarder and stops being a good forwarder, perhaps because its movement pattern changed or simply because it ran out of energy. As a 's EDD also remains unchanged, it is advertising itself to be a better forwarder than it is, potentially degrading the entire network's performance. We avoid the problem by taking into account the difference between the recorded ICT and the time elapsed since the last contact, replacing (1) with

$$d(v, c) = \text{edd}(c) + \text{ict}(v, c) + \text{ictVar}(v, c)H(\text{ictVar}(v, c)), \quad (3)$$

$$c \in V_v,$$

$$\text{ictVar}(v, c) = (\text{time} - \text{lastContact}(v, c)) - \text{ict}(v, c). \quad (4)$$

The ICT variation function (4) is positive if the time since last contact is in excess of the stored ICT value, and negative otherwise. In (3), H refers to the Heaviside step function, as only positive variation values should be considered.

Generally, messages are forwarded when a node with lower EDD is met. Although other factors may be taken into account when deciding whether to forward messages, a node with higher EDD is never considered a suitable forwarder, not only to minimize latency and energy waste but also as a way to prevent loops created by rapid variation of other metrics. The ICT of a link is an intermediate value, used only to determine a node's own EDD and not to make forwarding decisions—at that point, nodes will already be in contact, and the ICT is irrelevant.

3.2. Multivariate Utility Function. The concept of multifactor utility functions has been used before in opportunistic routing protocols, for example, [11]. The general idea is that it is possible to get a better solution by taking more information into account, which is normally true. There is another equally important advantage, in that it allows easy customization of the algorithm to the specific usage setting. For instance, in an underwater WSN equipped with barometric sensors, the pressure read is related to each sensor's depth. If messages are to be routed to the surface, a lower pressure may indicate a good forwarder.

The use of utility functions in CHARON is optional. An implementation can choose to use an empty utility function (i.e., one that returns a constant value), basing the decision only on the delay metric. If a utility function is defined, its results (the *score*) should increase with the desirability of the forwarder. In the case of EDD, on the contrary, lower is better—it is a negative indicator. As such, its symmetric should be used in the score's calculation. A basic utility function, using commonly available data, is (5). While the EDD allows us to determine the quickest path, the free buffer space is useful in preventing short-term buffer exhaustion of the intermediate nodes. Finally, the use of battery level serves to extend the lifetime of very desirable carriers, by gradually moving the load to other nodes as they start

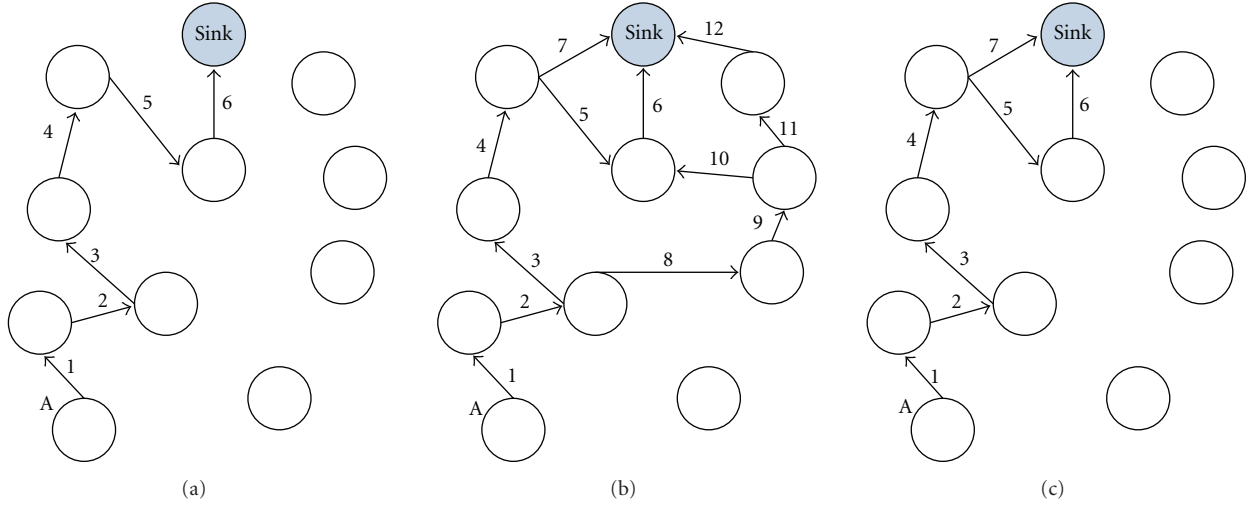


FIGURE 2: Different replication strategies (single copy, multi-copy and hybrid).

running out of energy

$$S(v) = -edd(v) + batteryLevel(v) + freeBuffer(v). \quad (5)$$

Depending on the expected EDD values and the range of the other parameters, they may have to be individually scaled in order to exert the desired influence on the final score. Note that, as there is a separate safeguard against forwarding messages to nodes with higher EDD, it is possible to build utility functions that do not use the EDD. Those functions are, however, replacing a possibly quantitative evaluation of the EDD (“is the other node’s EDD so much better that it compensates for our larger energy reserve?”) with a purely binary assessment.

There are no significant restrictions to the utility function other than having to return an integer value. They can be as simple as or simpler than (5), return a single value or a combination of several, or they can employ more advanced logic: anything that can be expressed in the language used for its implementation. Nevertheless, the use of simple functions is recommended to keep up with the stated goals.

3.3. Message Replication. There are two main replication strategies in widespread use. On the one hand, there are single-copy solutions, in which only one copy of each message is present in the network at any single time. On the other hand, there are multi copy solutions that replicate messages in network, resulting in the presence of several redundant copies. Single-copy strategies achieve high efficiency at the cost of reduced reliability; multi-copy strategies take the opposite approach.

Having efficiency as a goal, a mostly single-copy approach was chosen, with an additional optimization. In a traditional single-copy approach, a node forwards a message and subsequently erases it from its buffer. However, keeping an already held message bears no cost, neither in bandwidth nor in energy. As there is no real reason to remove such messages, they are kept in a special state: they are called *zombies*. Zombies are leftover copies from previously carried

messages and cannot be forwarded. They are kept while possible, and delivered only on the event that a node meets a sink, after which they are erased.

This solution creates a *hybrid* strategy, combining the advantages of single-copy schemes with some of the performance improvements made possible by multi-copy ones. A small comparison of the three strategies can be seen in Figure 2.

- (i) In the single-copy approach (a), the message flows through the network and is delivered, just once, to the sink. A message carried by a node that fails or wanders away is lost.
- (ii) In the multi-copy approach (b), the message is copied at each carrier node, and then forwarded. This results in an increase of the number of transmissions, as well as in the amount of buffer space in use. The number of paths being followed, as well as the number of simultaneous carriers, does, however increase delivery probability, which is reflected in the number of copies (three) delivered to the sink.
- (iii) In the hybrid approach (c), the message flows through the same path, but nodes on that path keep a zombie copy of the message. If any of these nodes come in contact with the sink, they deliver the message themselves. The problem is expressed in the following example: after forwarding a message (5), a node finds the sink, transmitting the zombie (7), thereby providing resilience against failures further down the path. While it is not the case in the example figure, it is possible that a zombie copy reaches the sink before the current holder of the message, in which case delivery latency is also reduced.

Zombies have negligible impact on routing efficiency (adding at most a single transmission per message), yet they share the same properties of message copies in that they increase fault tolerance and improve delivery statistics. They

TABLE 1: Example class configuration.

Class	Utility function	Replication strategy	TTL value
Monitoring	$S(c) = -\text{edd}(c) + \text{freeBuffer}(c) + \text{batteryLevel}(c)$	Hybrid	72 h
Alarm	$S(c) = 0$	Multicopy	12 h

do, however, take up buffer space: a zombie message, being a complete copy of its parent message, naturally requires the same amount of memory. The fundamental difference between a zombie and a copy comes into play when a node runs out of memory:

- (i) In a naive multi-copy strategy, a node has no way of knowing whether it can delete a message in case it runs out of memory. As this is a distributed problem, there are no guarantees that all nodes will not delete the same message, making it undeliverable.
- (ii) In the hybrid strategy, nodes generally carry some messages and some zombies. They know any zombie can be safely removed, as its parent message is being carried by some other node. Conversely, they know they must not delete their messages, because no other node carries them.

Despite the advantages of this approach, there are situations in which delivery probability must be maximized and, perhaps most importantly, latency needs to be minimized at any cost. The system supports a secondary purely multicopy mode for use in such situations. In this mode CHARON does not tag forwarded messages as zombies, continuing to forward them as before. While this mode does succeed in improving delivery statistics, it has a negative impact on the network as a whole if abused, and should only be employed when strictly required.

3.4. QoS Classes. Even within specific applications, there are sometimes messages with different requirements. A simple example is that of an agricultural monitoring WSN: while most messages probably contain only temperature, humidity and PH samples and are not urgent, there can also be alarm messages alerting the operators to a pest or a fire threatening production and requiring immediate attention. This coexistence of different requirements within the same network is the motivation for including quality-of-service (QoS) mechanisms in CHARON. Note, however, that the definition of QoS in this context is limited to the ability to provide different performance levels to different data classes. Resource reservation and service level guarantees are difficult (if not impossible) to implement in the target scenario and within the stated goals, and as such were not considered. In that sense, the service CHARON provides is always best-effort.

The customizability of some parts of CHARON was previously discussed, in what refers to the particularities of the deployment scenario. The system is even more adaptable as it can be customized for individual traffic classes within the same deployment. There are three independently configurable class-specific features: an utility function, a replication strategy, and time-to-live (TTL) value.

Depending on the chosen settings, the result can range from purely delay-based, multicopy routing with high overhead but low latency to very efficient, single-copy, energy-aware routing. While CHARON supports an unlimited number of classes, in the vast majority of cases two will be sufficient:

- (i) A low-priority class used for bulk monitoring data, configured with an energy-aware utility function and hybrid replication
- (ii) A high-priority class used for urgent alarm data, configured with no utility function and multicopy replication.

An example of such an arrangement is presented in Table 1, where different TTL values were also defined. The choice of TTL parameters should take into account the period during which data is useful. Alarm data is, by definition, urgent and—considering the wasteful mechanism being used to route it—should be set to expire as soon as possible.

Using this simple scheme, CHARON is able to provide multicopy-like performance on high-priority messages, as long as they are few and far in between, while still keeping global overhead at very low levels. Evidently, this is only true if alarm messages account for a small fraction of the total, or global performance will be severely degraded.

3.5. Time Synchronization. There are two main ways to obtain a global time reference on a WSN: listening to a broadcast source, such as GPS or FM signals, or running a synchronization protocol. While the former option is simpler and more precise, it requires additional hardware. Consequently, we decided to use a synchronization protocol.

There are already several high-precision time synchronization protocols designed for WSNs [14]. Most were designed for stationary networks and do not support opportunistic scenarios. The few that do, tend to behave poorly under high mobility and/or be of high complexity. They also introduce additional communication overhead in the form of synchronization messages.

Since CHARON's use for a time reference does not require high precision, a simpler solution may be used. The basic developed mechanism uses two fields on the periodic beacons broadcast by each node, and allows synchronization to the sinks' clock. When a beacon is received, a node updates its local reference using the algorithm presented in Algorithm 2.

Sink nodes have an age of 0, and are always used as sources. The *stepPenalty* parameter is indented to reduce the number of average synchronization steps, as there is an additional error introduced with each.

```

algorithm update_time (c) is
  if localTimeAge  $\geq$  timeAge(c) + stepPenalty then
    localTime  $\leftarrow$  time(c)
    localTimeAge  $\leftarrow$  timeAge(c) + stepPenalty
  end
end

```

ALGORITHM 2: Time synchronization algorithm.

The algorithm is about as simple as can be. There is no statistical treatment of time samples and transmission and reception delays are not compensated for. While accuracy of advanced algorithms can be in the order of microseconds, in this case it is around tens of milliseconds. Seeing that there is also no drift correction, the error will tend to rapidly increase with reference age. Current digital clocks can, however, maintain a useful reference for many hours or even days, which is good enough for most scenarios. Implementations should nevertheless monitor the age of the reference and move the system back to an unsynchronized state if it exceeds a given threshold, based on the used clocks' specified drift.

In addition to being used for power management, the global time reference is used to timestamp messages in a way that allows them to be sorted and correlated at the sink. This timestamp is also used to sort messages in the buffers and check for TTL expiration. Finally, it can be queried and used directly by applications.

3.6. Power Management. Regardless of how high an algorithm's routing efficiency is, it can not achieve good energy efficiency *per se*. Broadband radios are not only one of the largest consumers but can use as much or even more energy on idle listening than they do while transmitting. To save energy, this must be taken into account by turning off the radio when it is not necessary.

There are several possible radio power management approaches including synchronous [15] and asynchronous [16, 17] cycling, as well as more advanced, on-demand solutions such as wakeup radios [18]. Asynchronous cycling presents a suboptimal solution, requiring very short rounds that may inhibit advanced power saving modes, and can lead to long always-on periods if trying to transmit in the absence of neighbours. The use of wake-up radios is promising but requires additional hardware on most current platforms. This leaves synchronous cycling, which is generally a good solution although it requires a global time reference. The reference can either be provided by the CHARON-integrated synchronization mechanism or any other available source.

The global clock is used to generate synchronous rounds on all nodes. Rounds comprise an *on* time, when the radio is turned on and communication takes place, and an *off* time, when the radio is turned off and all system activity is suspended. Although only radio power management is handled, turning the radio off can (depending on the platform) allow the system to enter low-power modes, further reducing energy consumption. For that to happen,

the applications must also be synchronized and suspend their activities during off times, which is why we allow applications to subscribe to round generation events.

There are two parameters controlling radio rounds: the *round period* and the *round time*. The first describes the time between successive round starts, while the second describes the time the radio is left on in each round. The starting time of the following round (τ) is computed from the current time

$$\tau = (\text{time} \setminus \text{roundPeriod} + 1) * \text{roundPeriod}. \quad (6)$$

The node must wake up frequently enough not to miss too many connection opportunities and stay awake long enough to hear the neighbouring nodes' beacons and possibly forward messages. This requires some thought and analysis during the definition of sleeping periods, as these must be tailored to the scenario and take into account the expected movement speed and radio range. We expected that in most scenarios radios can be turned on for a few seconds every minute, leading to duty cycles around 10%.

When a node does not yet have a time reference available, synchronized radio cycling is impossible. We have decided not to implement a power-saving fallback mode, instead keeping the radio permanently on until a reference is acquired. While this might be seen as wasteful, in most cases nodes can be initially synchronized at the time of deployment, limiting the problem's severity.

3.7. Reference Implementation. In order to perform real-world testing and validation of CHARON, we have developed a reference implementation, for which we used Sun Microsystems' Small Programmable Object Technology (SPOT) [19] sensor nodes. These are relatively powerful nodes, featuring an ARM9 processor, 512 Kilobyte of RAM, 4 Megabyte of Flash memory and an 802.15.4-compliant CC2420 radio. Like most WSN nodes, they get their power from a battery, and ship with a sensor board containing a 3-axis accelerometer, temperature and light sensors, as well as LEDs, switches and several input and output pins. Instead of an operating system, the SPOT runs a bare-metal Java VM-Squawk [20]. CHARON is implemented as a bundle layer, sitting atop the included network stack and using the bundled datagram-based protocol (Radiogram) for all single-hop exchanges.

As a side effect, this implementation allowed us to assess the difficulty of deploying our solution in a real WSN, which we found very acceptable. The full implementation contains 32 classes and 1517 physical source lines of code (SLOC), excluding utilities and debugging functionality. The compiled suite stands at 47 KB, a value that, given the system's available memory, is barely noticeable.

4. Evaluation of Routing Performance

Opportunistic routing techniques are typically designed to be used in large mobile networks—conditions which are hard to reproduce in a laboratory. Simulation techniques were therefore used to evaluate the macroscopic behaviour of the algorithm, in conditions resembling the target scenario.

Simulations were performed using the Opportunistic Network Environment (ONE) simulator [21], an open-source Java-based simulator designed for evaluation of DTN routing algorithms. As the reference implementation was also written in Java, this option allowed for an easier conversion. Furthermore, it includes implementations of several algorithms that were used for comparison.

4.1. Base Scenario. Settings for the simulation were extracted from the target scenario we previously described. The area of movement was defined to be 80 km², in order to provide sufficient freedom of movement. A total of 60 nodes are initially distributed randomly throughout the area, resulting in a low node density of 0.75 nodes/km², as expected for our target scenario. A single static sink is placed in the centre of the map. We chose not to use multiple sinks, as not all protocols evaluated support this kind of setup. For an analysis of the impact of the number of sinks on the performance of an opportunistic routing solution, we refer the reader to [22].

There are six node groups, emulating a setting where different species or populations cohabit and exhibit different behaviour. Each group has a set of predefined waypoints, from which nodes select their next destination. Movement speed is randomly chosen from a predefined range (1.8 km/h to 18 km/h). Upon reaching a waypoint, nodes stop for a random length of time (0 s to 120 s). Nodes of some groups can never come in direct contact with the sink, as their movement area does not include the centre of the map. In the simulator used, this model of waypoint pools is not compatible with unrestricted movement. Instead, an approximation was implemented, in which nodes move on a tight lattice of possible paths, using a shortest path algorithm to reach their destination.

Each node generates fixed-size messages (200 B of raw physical layer data) with fixed periodicity (60 s). All nodes have 200 kB of buffer space, a reasonable size for current memory capacities. All messages have the sink as their destination. A single sink was used to allow fair comparison to protocols that don not support more than one. Radio range (40 m) and bitrate (250 kbit/s) were chosen to reflect typical values for 802.15.4 [23] radios used in WSNs. Each simulation runs for a period of 1 simulation day, during which 1440 messages are generated. Movement and event generation are regulated by a pseudorandom number generator. The generator seed is the same for multiple settings within each run, guaranteeing comparable results.

Table 2 presents a summary of the already listed simulation parameters. These default parameters are used in all simulations, except where otherwise noted.

Several of the simulation parameters may seem excessive namely, the message periodicity and the movement speed. These were chosen in order to guarantee meaningful results in simulations as short as 1 day, as the (real) time required to run longer simulations was unbearable. To further reduce variance and prevent artefacts caused by irregular movement, all results are averaged from multiple runs with different seeds.

TABLE 2: Default simulation parameters.

Area	80 km ²
Number of nodes	60
Run duration	1 d
Radio range	40 m
Radio bit rate	250 kbit/s
Buffer space	200 kB
Movement speed	1.8 km/h to 18 km/h
Idle movement time	0 s to 120 s
Message generation interval	60 s
Message size	200 B

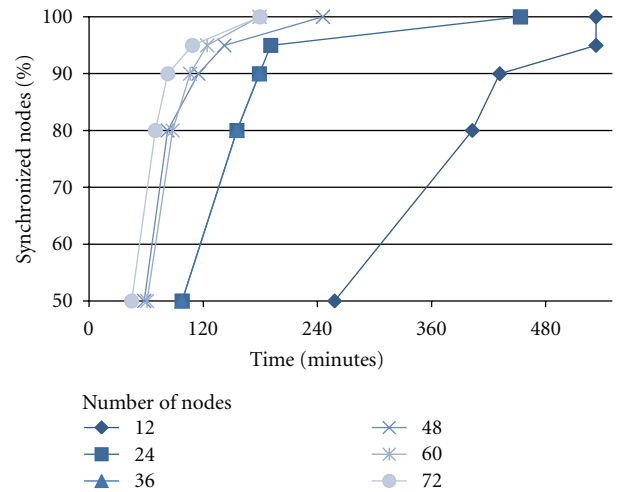


FIGURE 3: Evolution of network connectivity/synchronization during the startup phase.

4.2. Startup Phase. The calculation of our routing metric for a given node depends on the existence of a complete path between it and a sink. Hence, there is a startup phase in which nodes are not able to forward messages. During this period, nodes don't yet have a global time reference either; they are in an unsynchronized state. Since the system is designed for long-term deployments, this does not have a relevant impact on the network performance. Nevertheless, the transitory stage is interesting, and so we have measured the time to full network synchronization in our reference scenario for different number of nodes, with the results being presented in Figure 3.

Despite the size of our scenario and the constraints on node mobility, it can be seen that the time to full network synchronization is, even for the worst case, in the range of hours, confirming our assumption that, at least for this scenario, the duration of the start-up phase is not relevant. The results also show a clear dependence on the number of nodes, due to its effect on contact density and on the number of alternate paths.

It is also worth noting that, as expected, it generally takes longer to synchronize the last 20% of nodes than all the others. These are the nodes located farther away from the sink, and that require more communication hops and/or longer movement distances to reach it.

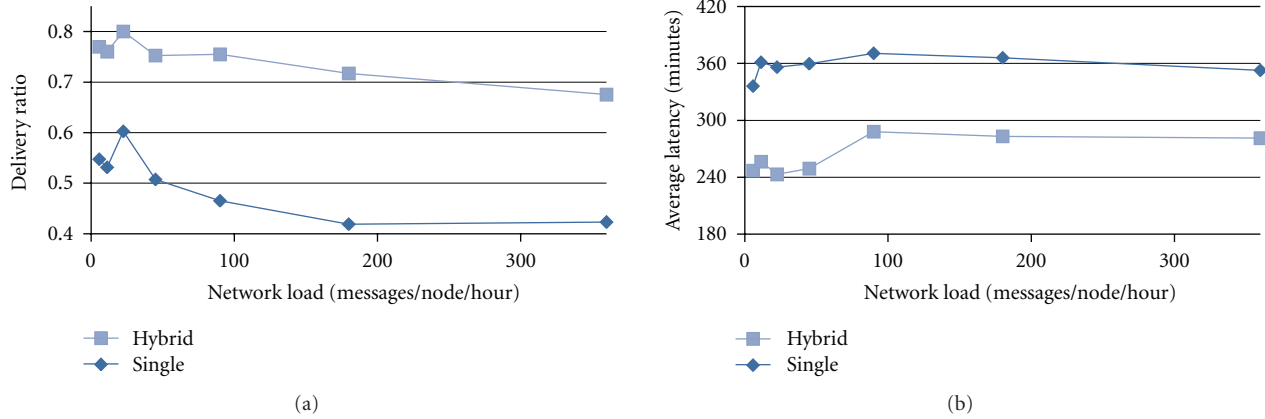


FIGURE 4: Performance impact of zombie messages.

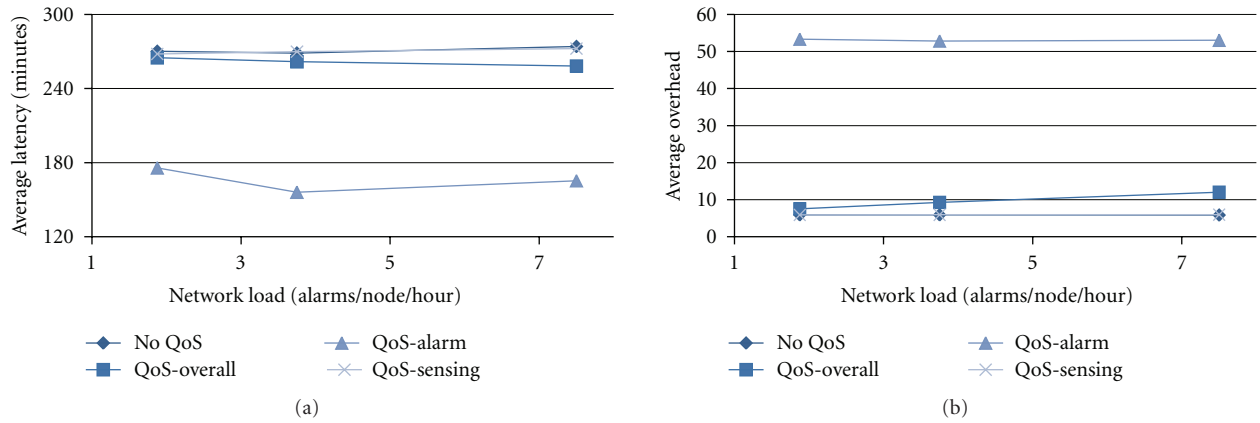


FIGURE 5: Performance impact of QoS mechanisms.

4.3. Replication Strategy. The hybrid replication strategy used in CHARON is based on the assumption that leaving previously carried messages as zombies is better than deleting them. To verify that assumption, the same simulation was carried out comparing a pure single-copy strategy and the proposed hybrid strategy. The simulation's results are presented in Figure 4.

As the network load increases, buffers start to fill up and messages are dropped or are not forwarded in a useful timeframe, leading to a decreased delivery ratio. Latency also shows a slightly downward trend with increasing network load, as when buffers are full, messages generated closer to the sink are more likely to be delivered.

Results show a very significant improvement on delivery statistics for the hybrid strategy, although the difference tends to be smaller for higher loads, when zombies start being deleted to make room for other messages. The results support our assertion that, by using zombies and increasing the number of alternative paths, delivery ratio and latency are improved.

4.4. Quality of Service. QoS mechanisms also need to be assessed in their ability to provide coexisting differentiated

service levels. To do so, a set of simulations were run in which nodes generated sensing messages (at the normal rate of 60 messages per hour) and alarms (at a variable rate, leading to different alarm/message ratios). Figure 5 presents the results in several series:

- (i) with QoS disabled, "No QoS";
- (ii) with QoS enabled
 - (a) alarm messages, "QoS-Alarm";
 - (b) sensing messages, "QoS-Sensing";
 - (c) overall outcome (alarm and sensing messages), "QoS-Overall".

The first aspect to note is that the lines for non-QoS traffic and sensing traffic mostly overlap, showing that in this load range, high-priority traffic does not negatively affect other traffic. Furthermore, alarm messages show a clear improvement in their latency, reduced by more than 40%. These improvements come at a cost of higher specific overhead (in line with multicopy approaches), yet global overhead remains low. This relationship holds for any scenario, as long as alarm messages make up for a small fraction of the total.

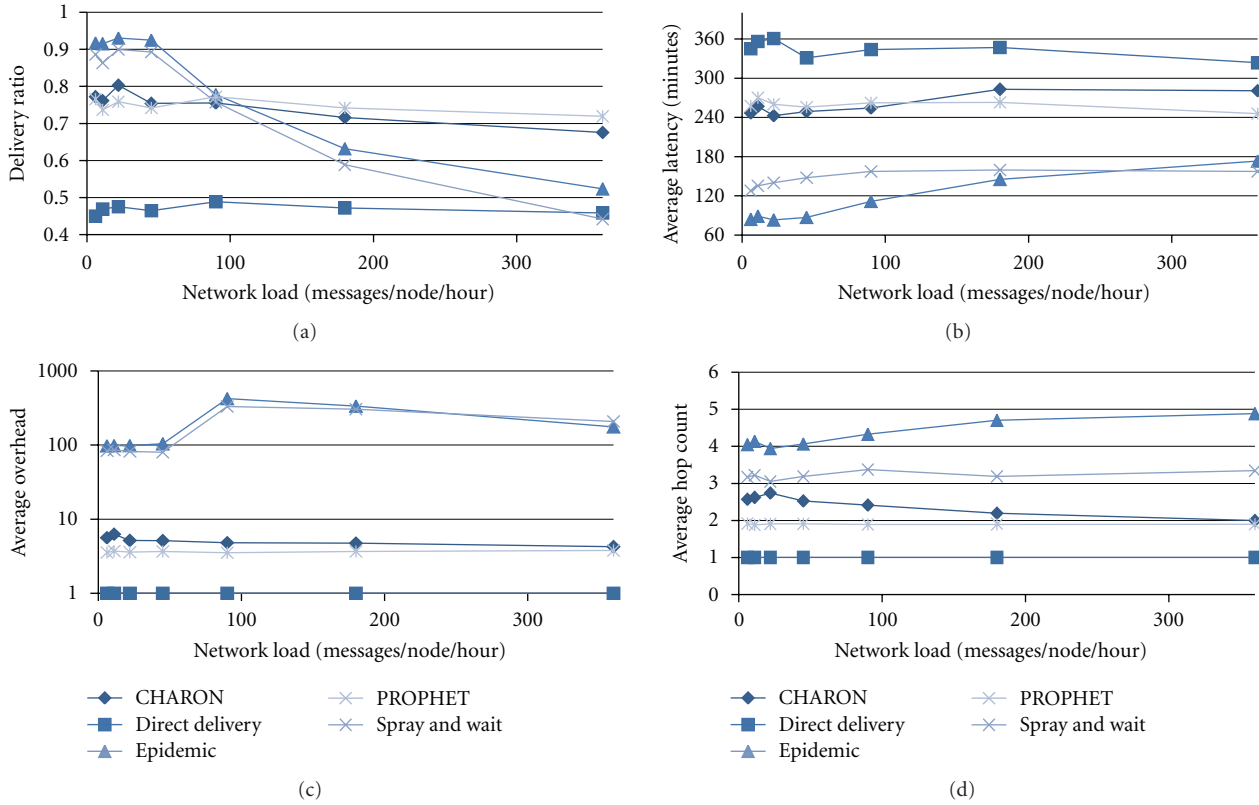


FIGURE 6: Performance comparison for various network loads.

4.5. Comparative Assessment. To be meaningful, the results obtained by CHARON must be compared to those attained by other routing solutions. To enable this comparison, we ran the same set of simulations using CHARON, spray and wait [8], epidemic routing [7], PROPHET [10], and direct delivery [24]. epidemic routing and PROPHET are multicopy protocols, and therefore we expect them to provide better results at lower loads. Spray and Wait is technically a multicopy protocol, but with a bounded number of copies per message (4 in this case), resulting in an intermediate solution, and the closest to CHARON—for that reason, it is generally not to be included when we refer to multicopy protocols below. Finally, direct delivery is the simplest possible single-copy protocol, allowing only direct transmission, when the source meets the destination. For fairness, neither CHARON nor any of the other protocols were highly tuned for this specific scenario.

The simulation compares algorithms’ performance for a wide range of network loads, and its results are presented in Figure 6.

Multicopy protocols behave better under low loads, resulting in very high delivery probabilities with low latency. As load increases, specifically around 90 messages per hour, resources turn out to be scarce and the situation is reversed, with CHARON and spray and wait taking the lead. With these two protocols and direct delivery there is little variation of delivery ratio with network load, due to the efficient use of resources. The massive difference in terms of efficiency

can be seen on (c), where PROPHET’s overhead is up to 70 times higher than CHARON’s. Latency is one of the strong points of multicopy protocols, with a sustained lead at every load. Differences in the latency and hop count trends—decreasing with network load for CHARON, but increasing for PROPHET and epidemic routing—are related to the different message dropping schemes: CHARON drops messages according to their global age (those generated farther away tend to be dropped first), while in the others they are dropped according to the order of reception (regardless of when they were generated).

It is interesting to compare these results with the ones obtained in the previous section. Under the exact same scenario, the alarm class on a QoS-enabled instance of CHARON can achieve delivery ratios above 0.80 and latencies in the order of 160 minutes, in line with those displayed by the best performers in the test. This means CHARON can provide top-quality service to messages that require it, while maintaining low general overhead.

Some conclusions can be drawn about each protocol’s performance relative to CHARON’s:

- (i) Direct delivery consistently obtains the weakest results, and is presented mostly as a baseline. Given that, in the base scenario, only some nodes are capable of reaching the sink, there is a preset limitation on the achievable delivery ratio; in a scenario with free movement it could perform better. It is, nevertheless, the most efficient protocol, having no overhead.

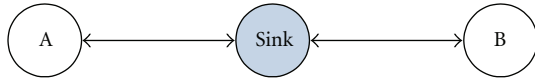


FIGURE 7: Synchronization test scenario.

- (ii) Spray and wait outperforms CHARON in many of the shared design goals. It is a very simple protocol, which achieves good results with low overhead. Its performance is nevertheless linked to the network diameter: in networks with different mobility patterns, in which the minimum number of hops required to reach the sink is greater, its performance-to-overhead ratio tends to degrade. This is not necessarily an obstacle to its use in real-world deployments, as many scenarios do feature rather low network diameter. On the other hand, it is more resilient than CHARON to changing network conditions and patternless movement, seeing as it does not make use of historic data.
- (iii) Epidemic routing and PROPHET show outstanding performance at low network loads, although the delivery ratio degrades quickly. They have an entirely different focus, and the high overhead makes them incompatible with the goals defined for CHARON.
- (iv) CHARON fulfils its objective of good delivery statistics with very low overhead. Delivery ratio is high, in line with spray and wait's and what realistically can be expected from a single copy protocol, although latency is somewhat high as well. The use of zombies seems to have limited impact under these conditions, as node movement is limited to separate areas, reducing the probability of a past carrier finding the sink. The QoS mechanism can make up for this handicap in case urgent messages need to be transferred, without a significant impact on the overall efficiency.

5. Evaluation of Additional Features

Contrary to routing, which is hard to evaluate on a real-world test bed, some of the algorithm features can only be meaningfully evaluated when running in real hardware. Using the previously mentioned reference implementation, we have performed some experiments meant to assess the performance of the time synchronization and power management mechanisms. These experiments, and the results obtained, are presented in this section.

5.1. Time Synchronization. To evaluate time synchronization error, a simple application was developed. Upon reception of a beacon, this application obtains the current global time from CHARON and sends it back to the sink. By having two nodes listen for beacons and comparing the timestamps each returns, it is possible to determine the pairwise clock offset. Figure 7 shows the test bed setup.

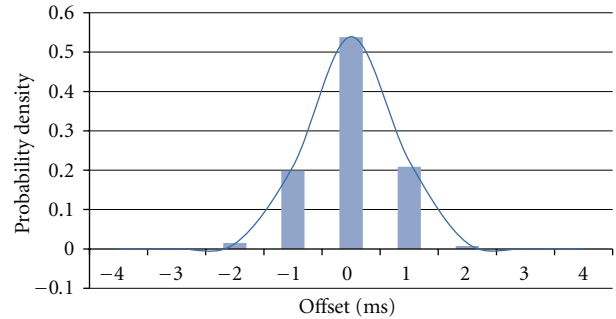


FIGURE 8: Pairwise clock offset distribution.

TABLE 3: Pairwise synchronization offset.

Offset (ms)	
$\bar{\epsilon}$	s
0,02	2,90

TABLE 4: Node lifetime under different power management configurations.

η	100%	70%	40%	10%
Lifetime (h)	14,63	18,00	28,35	79,71
Improvement	—	+23%	+94%	+445%

Direct comparisons against the sink's reference are not possible, as there is a nondeterministic delay between the time when a beacon is delivered to the sink's stack and the moment it is ready for processing at the nodes. The beacon does however reach all nodes at the same time (propagation delays are negligible at workbench distances), and under light loads is available for processing at approximately the same time. Nevertheless, the technique does introduce some measurement error.

The first experiment ran for one hour, with a one-second beacon period, resulting in 3600 samples. The resulting offset average ($\bar{\epsilon}$) and standard deviation are presented in Table 3.

The measured offsets are acceptable for most uses, as is the maximum absolute offset (22 ms). Figure 8 shows the detailed offset distribution which naturally approaches a normal distribution.

5.2. Power Management. The influence of CHARON's radio power management solution on the node lifetime was measured by having a single fully charged node run the test application while in permanent range of a sink. The sink recorded the arrival timestamp of every message, and the lifetime was extracted by subtracting the first from the last timestamps. The round period was set to 20 seconds and the round time was varied to achieve the duty cycles (η) presented in Table 4.

The use of radio power management has a clear effect on the global energy consumption. Not only is the radio turned off but, given that the entire library and the application itself are synchronized to the rounds, nodes are free to enter deep sleep mode. While a SPOT node in a fully active state has a

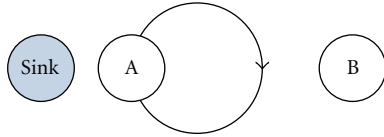


FIGURE 9: Round time test scenario.

current drain of up to 104 mA, in deep sleep it is reduced to just 33 μ A, an almost negligible value [25]. In previous experiments no strong connection was found between the position the node occupies and its energy consumption. This is justified by the fact that in the SPOT platform, energy consumption is lower in transmit mode than in receive mode [26], in which every node—regardless of its position—spends the majority of time. For this reason, and considering the long time required for each experiment, no tests were run with multiple nodes.

Turning off the radio does, however, carry an impact on network performance. To assess that impact, another experimental setup was created, and is shown in Figure 9. A node was installed on a rotating arm, with one other node and a base station placed on opposite ends of its circle of movement. The transmission power of the static nodes was tuned so that communication was only possible with the rotating node, and at very short distance. Therefore, this node acts as the single carrier, and features periodic movement.

A full rotation takes approximately 13 seconds to complete, given the motor speed used for the rotating arm and the CHARON round time was set to 1 second, in order to allow some flexibility in the definition of the round period. This leads to much faster mobility conditions than those expected for the target scenario, but still provides valuable results. Tests were run for different round periods, each lasting until 120 packets were received.

Looking at the results (presented in Figure 10) several conclusions can be drawn.

- (i) First, and as a general trend, one can see that longer round periods lead to longer delays, which is intuitive, as more contact opportunities are lost due to the radio being off.
- (ii) There is a steep increase in delay when the round period is increased from 5 to 10 seconds. With 5 second rounds, most rotations result in contacts, even if short, as that loosely fits the time the carrier spends in range of each node. When using longer periods, useless rotations become more frequent and the network performance takes a hit.
- (iii) When the round period is increased from 10 to 20 seconds, the average delay unexpectedly decreases. This illustrates a risk with the use of rounds in periodic movement situation: when the round period loosely fits the movement period (or a submultiple of it), we run the risk of synchronizing them in a way that prevents communication for long intervals.

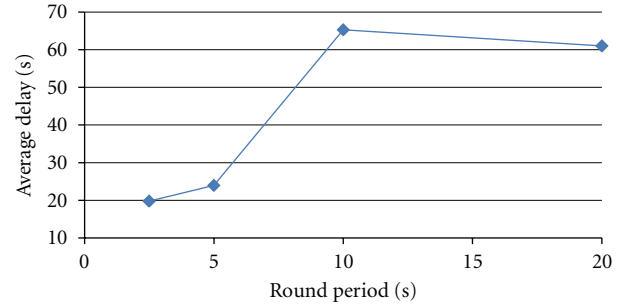


FIGURE 10: Average delivery delay for different round periods.

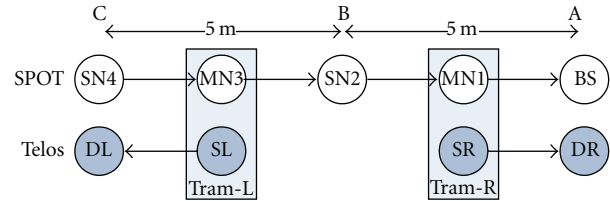


FIGURE 11: Test bed plan.

6. Experimental Characterization

So far, we have presented a detailed description of CHARON opportunistic approach and assessed its routing efficiency through simulation results. In this section, we extend and enrich CHARON analysis by discussing its performance in an experimental scenario involving real WSN nodes.

Beginning with the description of the network scenario and the experimental test bed where the tests were performed, we will now present a simple theoretical model strictly correlated with the mobility pattern, and able to predict the system performance. Based on this model, we will analyse the system behaviour, in particular in terms of message delivery delay, comparing the experimental evidence with the predicted results.

6.1. Test Bed Description and Mobility Pattern. The PeRT Lab open-space inside ISMB premises hosted the test bed utilized to realize a partially mobile network of WSN nodes running CHARON. The test bed plan is shown in Figure 11.

The network is composed of five SPOT nodes: four of them are configured as message sources and potential carriers while the fifth one plays the role of Base Station (BS) and is connected to a PC for data logging.

The nodes deployment results in a linear-constrained topology. Three nodes, that is, BS plus SN2 and SN4, where SN stands for static node, are positioned as follows: BS on the extreme right side, SN4 on the opposite extreme left side, and SN2 approximately halfway between BS and SN4. The remaining two nodes, called MN1 and MN2, are mobile (M stands for mobile). Figure 12 shows part of the test bed, including the trams and one of the ends.

In particular, MN1 moves between BS and SN2 while MN3 does the same between SN2 and SN4. To this aim, two LEGO Mindstorms NXT robots are attached to a hanging



FIGURE 12: Photograph of the test bed, showing the two trams approaching the center node (SN2), with SN4 and DL visible in the background.

cable and behave as trams (indicated as Tram- R and Tram- L , where R and L stand for right and left), endowing MN1 and MN3 with mobility capabilities. As an approximation, speed can be considered constant and equal for both trams. Minor and negligible fluctuations sometimes could occur due to the decay in battery level and the slightly different battery capacity.

The mobility is quite symmetric and, above all, repetitive, as a consequence of identical tram speed and internode distances. In order to eliminate such periodicity and to let the mobile nodes be in uncorrelated positions at a certain time instant, the trams are programmed to stop for periods of different duration. These stop periods occur after the trams' front and rear ends, equipped with touch sensors, detect an obstacle. In the case of Tram- R , the stopping period is set to $T_{\text{stop-}R} = 5$ seconds, and starts after hitting the obstacles positioned near BS or SN2. Likewise, $T_{\text{stop-}L} = 3$ seconds holds for Tram- L whose stops are in proximity of SN2 and SN4. After stopping, the tram resumes movement in the opposite direction.

The physical distance between BS and SN2 (and between SN2 and SN4) is around 5 metres. The transmission power was tuned to guarantee that these pairs of nodes are always out of the respective radio range and unable to directly communicate. For this reason, the sequence of carrier nodes that messages pass through along their path towards BS is highly constrained, almost deterministic, despite node mobility. Indeed, SN4 can solely forward messages to MN3, and SN2 can relay through MN1 only. When coming in contact with SN2, MN3 always finds it available as a good relay; however, when the two trams approach SN2 at the same time, messages can sometimes be forwarded directly from MN3 to MN1, skipping SN2 and gaining some efficiency.

The test bed includes a simple channel quality monitoring tool. This tool basically consists of a pair of XBow Telos nodes which exchange packets at high-frequency (in the order of tenths of milliseconds) and allows us to derive real-time information on link communication quality, based on metrics like RSSI, LQI and lost, packets, while CHARON is running on the SPOT nodes. We use that information as input data for deeper interpretation and analysis of CHARON dynamics, as detailed in the next subsection. In our test bed, we have duplicated the tool, by deploying two pairs of Telos. Concerning the first pair, one node has been positioned near BS and the other on the tram next to MN1; similarly, for the second pair, a node deployed near SN4 and the other on the tram with MN3.

Since distinct computers are used to store data from CHARON and from the monitoring tool, they have been synchronized using NTP so that all events are time stamped with a common reference. It is also worth noting that different channels in the ISM 2.4 GHz frequency band have been used for the CHARON nodes and for the monitoring tools, in order to prevent mutual interference among applications. On the other hand, the selected IEEE 802.15.4 channels, that is, 24, 25, and 26, have been chosen to minimize the risk of interference from Wi-Fi traffic [27].

6.2. Theoretical Analysis. We now introduce a simplified mathematical model that will be used in the next subsection for analysing experimental results obtained in the aforementioned test bed. The idea behind the model is to exploit the symmetry of the network topology, the periodic mobility pattern characterization and the resulting (almost) deterministic paths followed by messages, to predict the network behaviour on the longrun. The model equations derived in the following require some input parameters, which are estimated from the data collected by the monitoring tools.

6.2.1. Model Outputs Definition. The model provides the expected probability density functions (pdf) of delays suffered by messages from the moment they are generated to the moment of final delivery to BS. These functions are, respectively indicated as $D_{\text{BS-MN1}}^m$, $D_{\text{BS-SN2}}^m$, $D_{\text{BS-MN3}}^m$, and $D_{\text{BS-SN4}}^m$, where the superscript m stands for model and the notation in the subscript reports the last and the first node in the path of interest.

6.2.2. Model Inputs Definition. The model takes as input the following four quantities: $T_{\text{trip-}R}$, $T_{\text{trip-}L}$, T_{c-R} and T_{c-L} , measured in seconds. Considering the repetitive mobility pattern, $T_{\text{trip-}R}$ represents the time spent by Tram- R to complete a trip. $T_{\text{trip-}L}$ has the same meaning, applied to Tram- L . T_{c-R} is the duration of the contact between MN1 and BS or, equivalently, MN1 and SN2. A contact between two nodes occurs when they are in mutual range, regardless of the radio being on or off. An analogous definition holds for T_{c-L} , where the radio range concerns MN3 and SN2 or SN4. This definition implicitly assumes that all nodes are considered to have identical hardware (radio) features and that the radio

TABLE 5: Summary of model inputs and output.

D_{BS-i}^m	Predicted end-to-end delivery delay for messages generated by node i
T_{trip-x}	Time taken by tram x to complete a trip
T_{c-R}	Duration of MN1's contacts
T_{c-L}	Duration of MN3's contacts
R	Round period

propagation model is time invariant and depends only on the distance between transmitter and receiver.

6.2.3. Model Inputs Estimation. In general, the above quantities can be different from trip to trip due to many external factors; the variability is nevertheless expected to be negligible. In addition, real contact periods cannot be measured through direct observation. For our model purpose, we derive an estimation of the model inputs by first building a sample per trip and then averaging over all trips logged during the test bed session.

The duration of a single trip can be empirically calculated by processing the data collected by the monitoring tool; for this, the fast dynamics of the Telos application fit better than CHARON's. In particular, we need to identify special events that occur regularly once per trip and measure the inter-event period. In this way, an estimation of both T_{trip-R} and T_{trip-L} is achieved.

T_{c-L} can be derived through the following formula: $T_{c-L} = T_{stop-L} + T_{c-R} - T_{stop-R}$, which requires that first we obtain an estimation of T_{c-R} . SPOT logs are the only useful data source in this case because, despite both platforms being equipped with the same CC2420 radio chip, the actual transmission range is invariably different, even after manual tuning of the transmission power. Measuring a contact period is made a bit harder by the round-oriented operation of CHARON. Indeed, the passage through the border of the radio coverage area (in both directions) usually occurs while nodes are in the *off* period and there is no way to know precisely the time elapsed since the last transition of the functioning mode. Nonetheless, a weighted average of the number of sequential interactions during a contact allows us to build a reliable estimation provided that the number of trips is large enough.

6.2.4. Model Basic Assumptions. The final goal is to determine an analytical description for D_{BS-MN1}^m , D_{BS-SN2}^m , D_{BS-MN3}^m and D_{BS-SN4}^m , as a function of the quantities T_{trip-R} , T_{trip-L} , T_{c-R} and T_{c-L} . To reach this goal we need to make some simplifying assumptions so that the resulting model derivation is mathematically tractable. It is worth noting that such assumptions generally lead to optimistic model predictions.

We consider unlimited storing space for messages, which are therefore never deleted, and no communication failures at the application level. We assume that a single interaction during a contact is always sufficient to forward all the messages currently stored by the carrier node while, in general, the real behaviour depends on some CHARON parameters, for example, the TLL or the maximum memory

space devoted to data storage. In fact, we will see from our experiment that multiple interactions often occur, even when they are not expected. Finally, message transfer delays, as well as the time spent in completing other tasks like beacon transmission or reception, are neglected. As a consequence, multiples of R are the only admissible values for delivery delays.

6.2.5. Model Outputs Derivation. As observed before, the effective routes followed by messages targeted to BS are very constrained, almost deterministic, due to the deployment's linear topology, the transmission power preventing communication among static nodes, and the mobility pattern. Definitely, this scenario facilitates the model development since the delay characterization of messages originated by a certain node can be exploited to derive the analogous characterization for a farther node.

Suppose that MN1's position and movement direction at the start of a new round are known. Since messages generated by MN1 never pass through intermediate carriers, the delivery delay is deterministic. It can be computed considering the distance covered by Tram-R to enter the radio coverage area of BS (and, consequently, the time spent to that aim) and, if this happens while the radio is off, summing up the remaining time before it is turned on. MN1's initial position can be probabilistically characterized as the mobility pattern of Tram-R is fully known: it results in a uniform component due to the constant speed, superimposed to two Dirac deltas justified by the stops near BS and SN2. D_{BS-MN1}^m can thus be finally determined. In particular, it is intuitive to guess that null delay is experienced if MN1 is inside BS coverage area when the round starts, while maximum delay occurs when the contact with BS has just finished. The rest of the delay distribution is uniform, reflecting the mobility at constant speed. A summary of the parameters can be found in Table 5, and the complete characterisation of D_{BS-MN1}^m is reported in Table 6 together with D_{BS-SN2}^m .

Messages from SN2 always follow the same route, going through MN1, because SN2 is outside BS's radio range. The delay is minimized when MN1 is just on the border of SN2's coverage area, but still able to receive data from SN2, and is moving towards BS when a new round starts. We need to consider the time required to come in range of BS and, possibly, the residual time before the next *on* period starts. Maximum delay is determined in identical conditions, with the difference that SN2 and MN1 have just ended their communication window, so that an additional complete trip is required. Again, the tram's constant speed guarantees uniform distribution elsewhere.

TABLE 6: Characterisation of delivery delays for nodes MN1 and SN2. K is the largest integer such that the $(T_{c-R}+K \cdot R)/T_{\text{trip-R}} \leq 1$, $K_1 = \lfloor (T_{\text{trip-R}} - 2 \cdot T_{c-R})/2 \rfloor / R$ and $K_2 + 1 = \lfloor T_{\text{trip-R}} + (T_{\text{trip-R}} - 2 \cdot T_{c-R})/2 \rfloor / R$, with $\lfloor X \rfloor^+$ representing the smallest integer larger than X .

$D_{\text{BS-MN1}}^m$		$D_{\text{BS-SN2}}^m$	
Delay	Probability	Delay	Probability
0	$T_{c-R}/T_{\text{trip-R}}$	$K_1 \cdot R$	$[K_1 \cdot R - (T_{\text{trip-R}} - 2 \cdot T_{c-R})/2]/T_{\text{trip-R}}$
$i \cdot R$	$R/T_{\text{trip-R}}, i = 1, \dots, K$	$i \cdot R$	$R/T_{\text{trip-R}}, i = K_1 + 1, \dots, K_2$
$(K+1) \cdot R$	$1 - (K \cdot R + T_{c-R})/T_{\text{trip-R}}$	$(K_2 + 1) \cdot R$	$1 - [K_2 \cdot R - (T_{\text{trip-R}} - 2 \cdot T_{c-R})/2]/T_{\text{trip-R}}$

Things are more complex when considering $D_{\text{BS-MN3}}^m$ and $D_{\text{BS-SN4}}^m$, because messages generated by MN3 or SN4 sometimes have two alternative routes after MN3: while passing through SN2 is always possible, directly jumping to MN1 represents a shortest and more efficient path which is admissible only if the distance between MN3 and MN1 is smaller than the coverage radius when nodes wake up and the message is generated. However, from our model perspective, the assumption of instantaneous message transfers guarantees that such an event can be managed as if the message passes transparently through SN2, without incurring additional delay. We can restrict our analysis only to routes including SN2 without any loss of generality.

Another fundamental observation concerns the statistical independence between the position of MN1 at a random sampling time t and the position of MN3 position at the same time, regardless their initial positions. Note that this is true if t is taken over an infinite time period and is explained by the different stopping times $T_{\text{stop-R}}$ and $T_{\text{stop-L}}$. In light of this, we can claim that $D_{\text{BS-MN3}}^m = D_{\text{BS-SN2}}^m * D_{\text{SN2-MN3}}^m$ and $D_{\text{BS-SN4}}^m = D_{\text{BS-SN2}}^m * D_{\text{SN2-SN4}}^m$, where “*” denotes the convolution operation. To conclude, the analytical expression of $D_{\text{SN2-MN3}}^m$ and $D_{\text{SN2-SN4}}^m$ exactly coincides with $D_{\text{BS-MN1}}^m$ and $D_{\text{BS-SN2}}^m$ respectively, the only required modification consisting of T_{c-R} and $T_{\text{trip-R}}$ being replaced with T_{c-L} and $T_{\text{trip-L}}$.

6.3. Performance Evaluation. Implemented on the five SPOT nodes (BS, MN1, SN2, MN3, SN4) constituting our test bed, CHARON was tested for approximately 90 minutes. That duration represents a tradeoff between two opposing needs. On the one hand, the number of samples collected (e.g., delivery delays experienced by messages) or estimated (e.g., the duration of tram trips and contact events) during the experiment must be large enough to guarantee statistical reliability to processed data. On the other hand, the decrease of trams speed during the test, caused by unavoidable robot battery discharging, must be severely limited in order to keep as time unvarying as possible the estimations of the subsequent durations of trip periods.

CHARON settings were as follows during the test. The round time and the round period were, respectively, set equal to 2 and 10 seconds, while nodes in *on* mode exchanged beacons every 500 milliseconds. The two instances of channel quality monitoring tools, running at the two sides of the test bed, were launched with the transmitter node sending a new packet every 50 milliseconds.

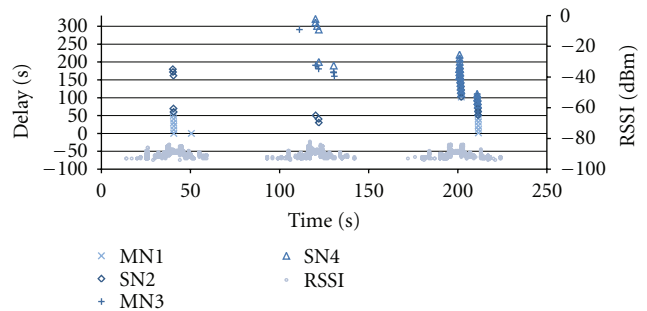


FIGURE 13: Detail of system events at BS, extracted from the test log, showing delivery delay of messages generated by SPOT nodes and RSSI of messages received by the channel quality monitoring nodes.

A zoom including about four minutes of system evolution is reported in Figure 13, where network events as captured by BS and the monitoring tool on the right side during three complete tram trips are displayed. As expected, SPOT messages are delivered to BS when the exchange of packets between the pair of Telos nodes is persistent and the channel quality is the best, as witnessed by collected RSSI values. However, while the time correlation between CHARON and Telos events is evident, in this test SPOT nodes seem to be characterized by a shorter radio coverage, as can be deduced by the very distant time instants in which nodes belonging to the two different platforms start a new interaction.

Figure 13 shows another and more important phenomenon. During each contact with BS, MN1 always needs more than one interaction (i.e., multiple rounds), typically 2 or 3, to succeed in delivering the messages it was storing. This leads to two relevant comments. First, the estimation of the contact duration T_{c-R} is necessarily comprised between 20 and 30 seconds. Indeed, three interactions cover a contact period of at least 20 seconds, while in case of two interactions the contact period cannot exceed 30 seconds. This is coherent with $T_{c-R} = 23.7$ seconds, as found by processing SPOT logs. $T_{\text{trip-R}}$ and $T_{\text{trip-L}}$ were instead estimated using Telos logs and the mean values resulted equal to 78.4 and 67.4 seconds respectively. Secondly, differently from what would be expected in light of current CHARON settings and differently from model predictions on the basis of the assumptions made, MN1 often concludes a contact with BS with some messages still stored and not delivered.

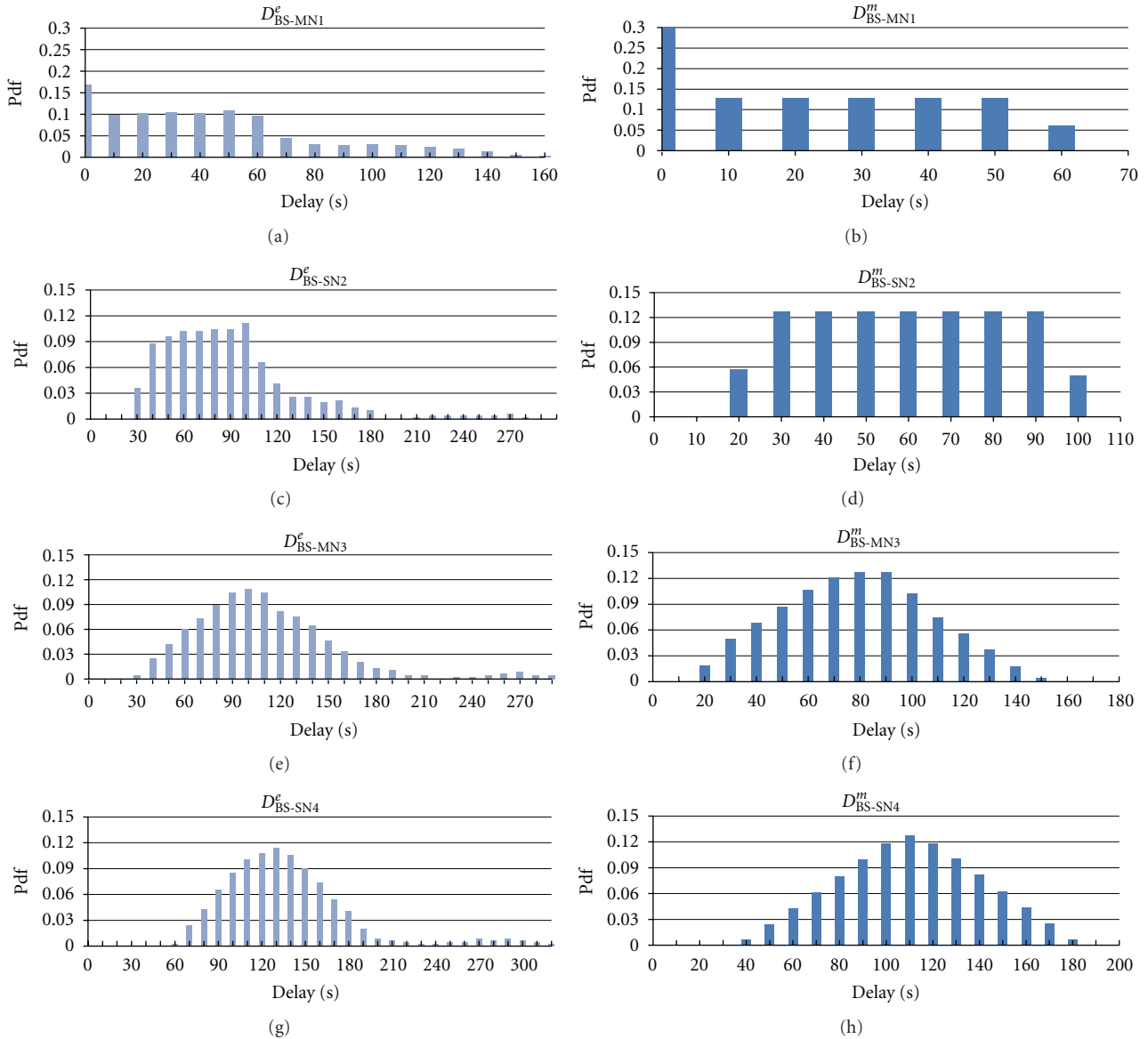


FIGURE 14: Experimental and predicted end-to-end delivery delay pdf.

These messages require a new contact, and thus a new tram trip, to find a new chance to be transferred. Looking at Figure 13, this can be clearly seen in the second trip, when no MN1-generated messages are delivered.

The fundamental metric on which our performance evaluation of CHARON is based is the latency experienced by messages, from their own generation time to the instant when they are delivered to BS. Since CHARON nodes are synchronized, and having the message generation and message reception events both time stamped, such latencies can be calculated for each packet using SPOT logs. Then, delays can be aggregated on a per-node basis and probability density functions of delays based on experimental data can be built. They are denoted respectively as D_{BS-MN1}^e , D_{BS-SN2}^e , D_{BS-MN3}^e and D_{BS-SN4}^e and are conceptually analogous to the correspondent functions analytically defined

through the model developed in the previous subsection. The comparison of the theoretical pdf with the experimental one can provide useful indications about system performance, possible inefficiencies and potential improvements.

The results obtained are displayed in Figure 14, composed of a pair of side-by-side plots for each of the four SPOT nodes (MN1, SN2, MN3 and SN4). As a general comment, the shape of the pdf achieved through the model is qualitatively similar to the shape of the twin pdf obtained with experimental data. This represents a clear validation of the theoretical model.

Experimental results for messages originated by MN1 show that the null latency is the minimum and also the one that occurs more frequently. This is confirmed by the model prediction as well as the approximately uniform probability

distribution characterizing the delay values in the range [10–50]. The model foresees maximum theoretical delays of 60 seconds, while larger delays are actually experienced by a few messages. This means that such messages are not delivered during the first useful contact between MN1 and BS, in contrast with the model assumption and with the expected application behaviour. More precisely, about one message over five (0.219 is the weight of the distribution tail comprising larger latencies than 60 seconds) requires at least an additional trip of the tram before being delivered. We can subtract to these delay samples multiples of 60 seconds, caused by additional trips, thus spreading the unexpected tail of D_{BS-MN1}^e over the theoretical range [0–60]. Then, by comparing the modified D_{BS-MN1}^e (not plotted) with D_{BS-MN1}^m , the coherence between experiments and model is further improved, as can be shown by the probability of null delay or, for instance, by the sum of the least squares, a common comparison metric, which decreases from 0.0224 to 0.0092.

Similar comments concern messages from SN2, since in that case only Tram-*R* is involved. The discrepancy regarding the minimum delivery delay (30 seconds by experimental observations, 20 seconds according to the model) is foreseeable and coherent with the knowledge that the model provides optimistic predictions.

The most significant *a posteriori* evidence when analyzing delivery delay densities of messages generated by MN3 and SN4 is that we were correct in postulating the statistical independence between the positions of the two trams at a random time, which the model derivation is explicitly based on. In fact, the triangular shape, which characterizes both the experimental and the theoretical curves, is the typical result of the convolution of two independent and uniformly distributed random variables. Since delivery delays of messages originated by MN3 and SN4 are built over the delays of nearer nodes MN1 and/or SN2, and since they are consequently obtained as sum of independent contributions, whose estimations suffer from unavoidable errors, the difference between minimum (or, equivalently, maximum) delays under experimental and theoretical analysis tends to increase. If other nodes were similarly deployed farther than SN4 along the linear chain, the effect would be still more evident, resulting proportional to the distance from BS, in terms of intermediate carriers. Quantitative values are also coherent: minimum delivery delays achieved through the experimental session are equal to 30 and 60 seconds for MN3 and SN4 respectively, compliant with 0 and 30 seconds observed for MN1 and SN2.

Finally, we observe that the weight of the tails of experimental pdf decreases as the number of intermediate carriers grows, being respectively equal to 0.219, 0.254, 0.120 and 0.092 for MN1, SN2, MN3 and SN4. Indeed, when considering nodes with several intermediate carriers along the path to BS, worst-case events, that is, largest message delivery delays, are experienced if worst-case less probable events simultaneously occur at each intermediate hop.

To conclude, the main system dynamics are well captured by the model and the minor discrepancies are easily justified by the simplifying assumptions, often leading to optimistic

predictions. One of the most impacting, in light of the experimental evidence, is the network load, in combination with the number of messages that can be held in intermediate buffers. We deduce this by the many events in which the time necessary to forward or definitively deliver all messages in the current round is not enough. Besides, it is worth remembering that possible losses of communication opportunities due to missed beacons or nondeterministic processing delays are not taken into account by the theoretical model.

7. Conclusions and Future Work

We have described the development and evaluation of an opportunistic solution for low-density WSNs, which we called CHARON. This approach is focused on reliability, simplicity, efficiency, and flexibility; more importantly, it aims not only for theoretical performance, but also real-world applicability. It is primarily built around a routing algorithm, but also includes additional atypical features.

Messages are routed by CHARON based primarily on the expected delivery delay, combined with information about the available resources or application-specific routing aids. A hybrid replication strategy is used for most messages to minimize resource waste. It works in a way similar to a single-copy strategy, but taking advantage of zombies, the inevitable copies left behind. Several uncommon features are also built-in to CHARON. Basic quality-of-service support makes it possible to serve coexisting applications with different needs. A time synchronization solution allows a global low-precision time reference to be shared by every node, and enables the use of synchronous radio power management, which can reduce energy waste, increasing node lifetime by up to 440% for a 10% duty cycle.

CHARON achieves better delivery statistics for high network loads than multicopy algorithms, with delivery ratio never falling below 0.65 in our simulation scenario. Its overhead is up to 100 times lower than that of the multicopy algorithms, resulting in a performance-to-overhead ratio up to 80 times better. While for light loads its results are below those achieved by multicopy algorithms, the overhead is still much lower. For urgent data, the built-in QoS mechanism can still provide multicopy-like performance, with the inevitable higher overhead. We also show that our hybrid replication strategy leads to significantly increased delivery statistics with minimal drawbacks.

Furthermore, we have performed advanced real-world evaluation of the developed solution, and compared the results obtained with those of a simple theoretical framework that has been shown to be able to predict the system's performance under some simplifying assumptions. Specifically, the model is able to predict the shape of the delivery delay pdf, although it has some bias towards the lower delays, explained by some optimistic assumptions, namely the one that bandwidth is unlimited and all buffered messages can be delivered in a single contact. Seeing as the model fits reality, it may be used to predict the solution's performance under different operating conditions, so long as the mobility patterns share some similarity.

Interesting topics for future research include the use of message integrity codes to provide trusted forwarding and the extraction of approximate location information from a node's history of contacts, assuming static nodes are present and georeferenced. The synchronization mechanism could be improved by taking into account more than just the freshest reference, making it more resilient. Lastly, more advanced treatment of delay metrics should be investigated. Nevertheless, improvements have a tendency to increase complexity, and a cautious cost-benefit analysis should be made. Finally, we would like to test the system under real operating conditions (e.g., in a silvopastoral monitoring WSN) in order to identify any practical weaknesses in the solution.

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