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CHARON: Convergent Hybrid-Replication Approach to Routing in Opportunistic Networks

Efficient Collection Routing for Low-Density Mobile WSNs

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To my grandparents

Para os meus avós

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Resumo

As Redes de Sensores sem Fios (RSSF) têm vindo a popularizar-se como soluções de monitorização remota, especialmente em cenários hostis, de difícil acesso, ou de outra forma complexos, em que a instalação de uma rede tradicional seria pouco prática. Algumas das aplicações vislumbradas, como a monitorização de vida selvagem, introduzem dificuldades adicionais ao incluir elementos móveis. Nestas circunstâncias, é necessário abandonar as técnicas de encaminhamento tradicional em favor das de encaminhamento oportunístico, que aproveita a mobilidade dos nós utilizando-os para transportar mensagens.

Esta dissertação aborda a temática do Encaminhamento Oportunístico em RSSFs. Começa por apresentar um resumo estruturado das soluções existentes, após o que é proposta uma nova abordagem: a Convergent Hybrid-replication Approach to Routing in Opportunistic Networks (CHARON). Esta abordagem tem como principais objectivos a simplicidade e a eficiência, com vista à aplicabilidade em situações reais. Usa como principal métrica de encaminhamento o atraso estimado, e suporta mecanismos básicos de Qualidade de Serviço (QoS), incluindo também funções de gestão de energia raramente encontradas noutras soluções. Em seguida descreve-se a implementação do protótipo do sistema em nós Sun SPOT, e, finalmente, são apresentados resultados de simulação e testes em ambiente real que demonstram que esta solução é capaz de conseguir um bom desempenho com elevada eficiência.

Palavras-chave

Redes sem Fios de Sensores, Comunicações Oportunísticas, Protocolos de Encaminhamento, Encaminhamento Oportunístico, Redes Tolerantes a Atraso, Eficiência Energética

Abstract

Wireless Sensor Networks (WSNs) have been slowly moving into the mainstream as remote monitoring solutions – especially in hostile, hard-to-reach or otherwise complicated scenarios, where deployment of a traditional network may be unpractical. Some of the envisioned applications, such as wildlife monitoring, introduce an additional difficulty by featuring mobile elements. In these circumstances traditional routing techniques must be abandoned in favour of Opportunistic Routing (OR), which uses mobility to its advantage by having nodes carry around messages.

This dissertation addresses the issue of Opportunistic Routing in WSNs. An overview of existing solutions is presented, followed by the description of a new Convergent Hybrid-replication Approach to Routing in Opportunistic Networks (CHARON). This approach is focused on simplicity and efficiency, aiming for real-world applicability. It primarily routes messages based on estimated delay, and supports basic Quality of Service (QoS) mechanisms. It also provides built-in radio power management, a seldom found feature. A reference implementation of CHARON is then presented, accompanied by simulation and real-world test results that show this solution is capable of achieving good delivery statistics with high efficiency.

Keywords

Wireless Sensor Networks, Opportunistic Communications, Routing Protocols, Opportunistic Routing, Delay-Tolerant Networks, Energy Efficiency

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List of Acronyms

AP	Access point
APS	Adaptive Pigeon Scheduling
CAR	Context-Aware Routing
CHARON	Convergent Hybrid-replication Approach to Routing in Opportunistic Networks
CLDC	Connected Limited Device Configuration
DTN	Delay tolerant network
EDD	Estimated delivery delay
EWMA	Exponentially weighted moving average
FIMF	Ferry-Initiated Message Ferrying
FRESH	Fresher Encounter Search
GCF	Generic Connection Framework
GREP	Generalized Route Establishment Protocol
HoP	Homing Pigeon
HoP-DTN	Homing Pigeon based Delay Tolerant Network
ICT	Inter-contact time
LP	Linear programming
MANET	Mobile ad-hoc network
ME	Micro edition
MF	Message Ferrying
MIC	Message integrity code
MULE	Mobile Ubiquitous LAN Extension
MV	Meetings and Visits
NIMF	Node-Initiated Message Ferrying
ONE	Opportunistic Network Environment
OR	Opportunistic routing
PROPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
SCAR	Sensor Context-Aware Routing
SLOC	Source lines of code
SPST	Shortest Paths in Space and Time
STR	Space-Time Routing
SWIM	Shared Wireless Infostation Model

TTL	Time to live
VM	Virtual machine
WLAN	Wireless local area network
WSN	Wireless sensor network

1 Introduction

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

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 between 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 – what is called an *opportunistic* communication.

Opportunistic communications present a challenge to several network layers, most notably routing, as the network topology becomes extremely volatile and complete end-to-end routes may never even exist at any single point in time – a situation falling within the realm of disruption and delay tolerant networks (DTNs). While opportunistic communications in general, and opportunistic routing (OR) in particular, are challenging in and of themselves, applying these principles to WSNs presents additional problems and specificities which must be carefully considered.

The primary concern with WSN design is the chronic lack of resources. Heavily constrained resources typically include storage space, execution memory, processor cycles, and transmission power, just to name a few. 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 networks running. While several energy harvesting systems are available, they are usually expensive and sometimes unsuitable for the operating conditions, and have found limited use among current deployments. Even when a node is equipped with an energy harvesting device, the energy provided might not be enough to sustain it in a high-power state, requiring implementation of software power management solutions.

The previously stated limitations lead to a scenario in which existing OR approaches may be less than ideal for this class of networks. Assumptions on acceptable algorithmic complexity must be reviewed, as must those about the available information and the number and size of signalling messages. Availability of unlimited buffer space, another popular assumption, must also be handled with caution, as this can present a major problem in the context of WSNs.

1.1 Motivation and Goals

This dissertation aims to contribute to the state of the art in opportunistic routing protocols specifically tailored for WSN use. Routing in WSNs, as previously stated, always has application-specific requirements and constraints, and it is close to impossible to design a good general-purpose algorithm.

Many of the existing protocols 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 [1].

This dissertation defines a realistic target scenario, and proposes a solution that can be used to effectively and efficiently route messages in that setting, without compromising its simplicity and, consequently, its feasibility. The system is also intended to be fairly flexible, supporting applications with different requirements.

The proposed approach is named CHARON – Convergent Hybrid-replication Approach to Routing in Opportunistic Networks.

1.2 Contributions

The full contributions of this dissertation are:

- A brief survey of existing opportunistic routing solutions, both general-purpose and WSN-specific.

- A low-overhead opportunistic routing algorithm for use in low-density, highly-mobile WSNs.
- A simple opportunistic synchronization and radio power management technique, integrated with the routing solution.
- A reference implementation of the system using real WSN nodes.

1.3 Document Structure

The remainder of this dissertation is organised into six main chapters. The following chapter, Chapter 2, presents a brief overview of the current state of the art of opportunistic routing approaches suitable for use in WSNs. A brief outline of each approach is provided, as well as the available performance data, and the different approaches are compared in their main characteristics. Chapter 3 describes the target scenario, and the main architectural requirements for a network operating in this scenario. In the main chapter, Chapter 4, the algorithm design is presented, its features are described and the choices made are explained. Chapter 5 presents the reference implementation, and Chapter 6 provides the results of the algorithm's evaluation. Finally, Chapter 7 concludes the dissertation with some final considerations and suggests directions for future work.

2 State of the Art of Opportunistic Routing

In this chapter, the current state of the art in OR protocols for mobile networks will be reviewed. While some of these protocols were designed for use in WSNs, others were not, but are nevertheless applicable. After presenting the two widely-used categorisations, the most representative existing protocols will be briefly explained. Finally, a classification table will be presented, followed by some significant conclusions.

2.1 Opportunistic Routing Approach Categorisation

2.1.1 Categorisation Based on Network Infrastructure

This first categorisation concerns the required structural aspects of the network [2], and defines two main categories:

- Networks without infrastructure
- Networks with infrastructure

Networks featuring some kind of infrastructure can be further divided into two additional sub-categories:

- Networks with fixed infrastructure
- Networks with mobile infrastructure

This so-called infrastructure is typically composed of more powerful nodes, featuring higher computational capability, higher storage capacity or higher energy reserves, for instance. Nodes that are part of a mobile infrastructure may move randomly, according to pre-defined paths or even on demand, driven by the networks' needs.

An important distinction must be made between the meaning of the term *infrastructure* in this context and in the context of wireless access networks. In a wireless local area network (WLAN) using infrastructure mode, devices can only communicate through an access point (AP), as opposed to the ad-hoc mode in which devices communicate without central coordination. This is not the case with infrastructure-equipped WSNs, which are still considered ad-hoc networks, as their nodes do exchange data directly and independently.

2.1.2 Categorisation Based on Network Evolution

The second categorisation divides networks according to the temporal evolution of their topology [3]. The two categories are:

- Networks with deterministic evolution
- Networks with stochastic evolution

Network evolution is considered deterministic when the future topology is known or predictable. In this case, delivery routes can be planned ahead of time. Otherwise, if the network evolution is regulated by a stochastic process[1], reliably predicting the future topology is impossible. Thus, routing decisions cannot be made in advance and are, at best, informed guesses.

2.2 Existing Approaches

2.2.1 Epidemic or Random Forwarding Approaches

2.2.1.1 Epidemic Routing

Epidemic Routing [4], one of the first proposed OR 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.

2.2.1.2 Two-Hop Forwarding

Two-Hop Forwarding [5] is a simple routing approach in which messages are relayed through a single intermediate node, thereby imposing a limit of two hops. A source node generating a message sends it to a randomly chosen relay, which stores the message until delivery to the destination is possible.

[1] A stochastic process is, informally, a process whose behaviour can be described by the evolution of one or more random variables.

While still a very conservative approach, and limited to scenarios of high node mobility and/or small network diameter, it manages to significantly improve network throughput with a low energy budget, achieving results close to the maximum limit imposed by the interference model used in the authors' evaluation. It is, however, ill-suited for applications with delivery deadlines because message delay under this scheme tends to be very high.

2.2.1.3 (p,q)-Epidemic Routing

The authors of (p,q)-Epidemic Routing [6] define a class of routing schemes in which messages are forwarded in a probabilistic manner, with p (respectively q) being the probability of a relay node (respectively source node) transmitting a packet to another node when they meet. Several previous algorithms are special cases of (p,q)-Epidemic Routing, such as conventional Epidemic Routing (p=1, q=1), and Two-Hop Forwarding (p=0, q=1), as well as direct source-destination delivery (p=0, q=0).

The authors conclude that Two-Hop Forwarding is the most energy-efficient scheme, but very wasteful of buffer space. In terms of buffer requirements, either Epidemic Routing or a scheme with small p are the most efficient, depending on the number of nodes in the network.

2.2.1.4 Spray and Wait

Spray and Wait [7] 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.

The authors' evaluation results show better energy efficiency and lower delay than the other tested stochastic protocols, including Epidemic Routing. Its performance is, nevertheless, tied to the network diameter, and very wide networks may require high number of copies, with a considerable decrease of efficiency.

2.2.1.5 Spraying

The Spraying algorithm [8] aims to reduce the number of broadcast messages by restricting forwarding to the vicinity of the last known location of the destination node. While it is possible that the node has since moved, a reasonable assumption is made that it is not likely to have moved too far. Under that assumption, the packet is first unicast to a node close to the destination's last known location, and then broadcast in the area.

This protocol requires knowledge of each node's current location. The authors, finding existing location solutions unsuitable, propose a rudimentary scheme based on the existence of *location managers*, to which both location update and location request messages are sent. It is also worth noting that this is not a predictive protocol, as it bases its decisions solely on the last known location instead of trying to determine trajectories or other possibly useful information.

2.2.1.6 Infostation

In the Infostation model [9] communication only takes place between nodes and static infrastructure elements named Infostations. Infostations act as gateways, are permanently connected, and are capable of providing a high bandwidth service. A node wanting to send a message has to move close to a nearby Infostation and upload it. It is then the Infostation's responsibility to deliver the message to the final destination, which is always outside the considered opportunistic network.

2.2.1.7 Shared Wireless Infostation Model

The Shared Wireless Infostation Model (SWIM) [10] extends Infostation by including node-to-node forwarding. Message routing between the nodes follows an epidemic model, but instead of aiming at a specific destination, any of the Infostations may serve as the termination node for any given message.

The authors present an example application consisting of a whale monitoring network with fixed or mobile infrastructure, and extract some conclusions from the results. The SWIM model manages to decrease delivery delays by 1.6 to 3.5 times when compared to Infostation, taking a slight penalty on the transmission bandwidth and storage requirements.

2.2.1.8 Data MULEs

The authors of Data MULEs [11] 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.

2.2.2 History or Prediction-based Approaches

2.2.2.1 ZebraNet

ZebraNet [12] [13] 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 (which, from now on, will be referred to as the ZebraNet 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.

Based on simulation results, the authors report that by exploiting indirect connectivity, the system achieves a six-fold decrease on the radio range needed to keep the network fully connected, and halves the radio range required to achieve a 100% delivery success rate. They also conclude that the history-based protocol generally works better than flooding while maintaining energy consumption levels similar to direct transmission.

2.2.2.2 MV Routing

MV Routing [14] uses the same pair-wise message exchange principle as Epidemic Routing, but improves on the method used to determine which messages to transmit. Instead of flooding its neighbours, each node uses observation data on the *meetings* between nodes and *visits* to locations (hence the name MV) to compute a delivery probability for every other node on the network.

When two nodes meet, the summary vectors contain not only the message identifiers but also the computed delivery probability. Nodes compare their own and their pair's values, and only request messages for which their probability is higher. These messages are then erased from the source node, preventing message duplication.

2.2.2.3 PROPHET

The Probabilistic ROuting Protocol using History of Encounters and Transitivity (PROPHET) [15] 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 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.

2.2.2.4 Context-Aware Routing

Context-Aware Routing (CAR) [16] is a hybrid protocol, featuring both synchronous and asynchronous routing mechanisms. The synchronous delivery mechanism – used when at the time of packet arrival there is an end-to-end path between the receiving node and the destination – assumes a synchronous routing protocol is running on each network partition, and forwards the packet according to that routing protocol. Otherwise, the next best hop is selected by means of an application-specific delivery probability metric. Delivery probabilities are determined by local analysis of several bits of context information, such as the degree of mobility and the battery level. Kalman filters are used to predict context evolution, and the resulting probabilities are periodically sent to the other nodes in the partition, where they are used to make routing decisions.

Simulation results show CAR having a lower delivery rate than that of Epidemic Routing but higher than pure flooding, and doing so with less message duplication, and hence better efficiency. Contrary to Epidemic Routing, the number of exchanged messages is approximately constant in regards to the buffer size, indicating better scalability.

2.2.2.5 Sensor Context-Aware Routing

Sensor Context-Aware Routing (SCAR) [17] bears some resemblance to CAR, but was specifically thought for use in WSNs. In particular, it shares the same prediction model, using Kalman Filters, but the communication and replication aspects were redesigned in consideration of the resource limitations, high data traffic and high fault rate of WSNs, as stated by the authors. 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.

The authors' evaluation only compares SCAR to a random choice protocol, achieving better results for all but one metric: delivery ratio when using high message replication factors.

2.2.2.6 MobySpace

MobySpace [18] introduces the idea of high-dimensional Euclidean spaces to OR. A Euclidean space named MobySpace is constructed upon the nodes' mobility patterns, with axes representing some interesting event, such as previous encounters or visits to locations, and the distance along the axis measuring the event probability. Two nodes with similar experiences are close to each other on the MobySpace. When forwarding a message, the next best hop is the one closer to the destination, according to some distance measure, which can be a Euclidean distance, Canberra distance, Cosine angle separation, Matching distance, or any other which suits the application and network requirements.

2.2.2.7 Space-Time Routing

Space-Time Routing (STR) [19] algorithms take into account both the distance to the destination node and the age of the routing state. Being a family of algorithms, there are many possible solutions, with different metrics and weights. Two possible approaches by the same authors are Fresher Encounter Search (FRESH) [20] and Generalized Route Establishment Protocol (GREP) [21]. FRESH is a simple protocol which only considers temporal information. Nodes keep a record of their last contact with every other node, and forward a message if they encounter a node that had a later contact with the destination. GREP integrates this idea with traditional distance vector routing, causing messages at each hop to either advance in space along their current route, or in time onto a fresher route.

2.2.3 Movement Control Approaches

2.2.3.1 Message Ferrying

Message Ferrying (MF) [22] is a mobility-assisted approach which uses special nodes called *message ferries* to enable communication between nodes on the network. These ferries move around carrying data, such as their real-life counterparts carry passengers and vehicles. The main idea introduced in MF is the active use of mobility to facilitate communications, according to two possible movement schemes: Node-Initiated MF (NIMF) and Ferry-Initiated MF (FIMF). In NIMF, the ferry path is known, and nodes waiting to transmit move closer to the path in order to meet up with the ferry. In FIMF, it is the ferries that adjust their trajectories, moving towards nodes with communication needs, following short requests transmitted over a long-range radio.

2.2.3.2 Inter-Regional Messengers

Inter-Regional Messengers [23] use a different model in which messengers (akin to message ferries) are owned (either permanently or temporarily) by a single network region, and only carry messages whose source or destination is their owner. Two ownership schemes are proposed: regional ownership, in which a messenger is permanently owned by a region, performing two-way trips between that region and the destination, and independent ownership, in which a node sent to a given region becomes said region's property until it is sent to a new one. The authors experimented with several scheduling strategies, namely periodic (fixed periodic departure times), on-demand (messenger is dispatched whenever there is a message to send) and storage-based (messenger is sent when buffer occupation reaches a predefined level).

Simulation results show that, as expected, optimal ownership schemes and scheduling strategies depend on the network conditions and requirements. On-demand scheduling guarantees the lowest delay, while storage-based scheduling is usually the most efficient. Periodic scheduling provides a middle ground, but there is some difficulty in defining the right period. As for the ownership schemes, under the proposed scenario, independent messengers achieve double the efficiency and half the cost of the regional scheme mainly by avoiding the return trip.

2.2.3.3 Homing Pigeon based DTN

Homing Pigeon (HoP) based DTNs (HoP-DTNs) [24] are similar in model to Inter-Regional Messengers, but are built on a theoretical framework considering message lifetimes and simplistic assumptions. Each node has its own messenger (here called pigeon, in reference to traditional homing pigeons), which is dispatched when s messages are buffered, and visits all the messages' destination nodes on a single trip, before returning to its owner. Further work by the authors [25] introduces the concepts of regions and region-owned pigeons, also considering the existence of multiple pigeons per region. In addition to the already discussed on-demand and periodic scheduling strategies, the authors propose a new algorithm named Adaptive Pigeon Scheduling (APS) which aims to increase cooperation between pigeons in the same region and decrease average message delay.

APS is shown to consistently achieve lower delays than the other approaches, regardless of message generation rate, pigeon speed and number, but at the cost of generally lower energy efficiency when compared to periodic scheduling.

2.2.4 Coding-based Approaches

2.2.4.1 Erasure Coding

Erasure coding works by splitting a message into k blocks and then expanding them to n blocks to be transmitted in such a way that the reception of any k of the n is enough to recover the original message. Several erasure coding based approaches have been proposed, such as [26] [27] [28].

In [26] a routing approach based on erasure coding is presented. Building on the existing 2-hop routing protocol (with added message replication), the authors propose a variation in which the sending node codes the message into k parts, replicating it by a factor r, and transmitting it to kr different relay nodes. The base assumption is that it is likely that k of the kr nodes meet the destination node sooner than just 1 of the otherwise r nodes (maintaining the same replication factor), so delay can be reduced while maintaining the same efficiency (the kr blocks are the same size as just the r message copies).

Simulations were conducted using real world mobility traces from the ZebraNet project. Results obtained under the assumption of infinite buffer space, replication factor $r = 2$ and splitting factor $p = kr = \{8,16,32\}$ show this approach to have lower delay variance than 2-

hop routing with the same replication factor, also beating every other tested protocol except for pure flooding. The 50th percentile delay is generally higher than with the other approaches, showing that very low delays are uncommon under this scheme and the majority of messages are delivered at an almost constant, albeit moderate, delay.

2.2.4.2 Network Coding

Network coding is an approach in which intermediate nodes can combine packets using a given invertible function before forwarding. As an example, in a communication involving two nodes (*A* and *B*) and an intermediate node *C*, in which node *A* sends a message *x* and node *B* sends a message *y*, node *C* can combine them into a single message $w = x \oplus y$, which it then broadcasts to both nodes. Each node, when receiving message *w* can decode it using its own sent message to recover the other, halving node *C*'s transmission needs.

A network coding routing algorithm is presented in [29]. In this approach, packets are transmitted in the form of an encoded information vector and a separate encoding vector used to fill a decoding matrix. When a node receives a packet of which it is not the destination, it uses the matrix to generate *d* new vectors (*d* is referred to as the *forwarding factor*) that are broadcast to its neighbours. When a destination node receives enough packages, it can decode the original information.

Coupled with a generation management mechanism and an information ageing mechanism to reduced the decoding matrix size, this algorithm is not only implementable in WSNs but manages to outperform probabilistic routing in regards to the packet delivery ratio and the average packet delay using the same forwarding factor or, alternatively, achieve a lower overhead for the same delivery requirements. Networks such as ZebraNet – where all packets are destined to a sink and never to another sensor node – can benefit even more from network coding, as there is no need for the nodes to be able to decode the messages and so packets can be combined arbitrarily.

2.2.5 Modified Shortest Path Approaches

2.2.5.1 Shortest Paths in Space and Time

The Shortest Paths in Space and Time (SPST) algorithm [30] works on the assumption that it is possible to accurately predict node motion over at least a finite time interval. The network is modelled as a *space-time graph*, with end-to-end paths existing *over time*, and nodes select the next best hop by looking at derived space-time routing tables that include not only current but also future neighbours. The selection algorithm, built with the aim of minimising latency, is a Floyd-Warshall adaptation that takes into account both the destination and the message arrival time.

Simulation results show that SPST generally behaves better than Epidemic Routing and the other tested algorithms, providing both lower latency and higher message delivery success ratio while achieving reduced message duplication.

2.2.5.2 Knowledge Oracles

In [31] several algorithms are proposed, all based in the concept of *Knowledge Oracles*, each of the four representing some knowledge of the network at any point in time. The *Contacts Oracle* contains information about node contacts; the *Contacts Summary Oracle* contains aggregate statistics of these contacts; the *Queuing Oracle* contains information about buffer occupation at each node; finally, the *Traffic Demand Oracle* contains information about traffic demands at each node.

The used algorithm depends on which oracles are available. If all of them are, then finding the best route is a Linear Programming (LP) problem. If at least the *Contacts Summary Oracle* or the *Contacts Oracle* is available then a modified Dijkstra's algorithm is used, with the cost function depending on the specific combination of oracles.

2.3 Approach Classification and Comparison

In Section 2.1 the two most common classification criteria for WSNs were introduced. Table 2-1 lists, for each discussed protocol, its classification under each criterion.

TABLE 2-1: CLASSIFICATION OF EXISTING ROUTING APPROACHES

Approach	Network infrastructure		Network evolution		Working principle
	Fixed	Mobile	Stochastic	Deterministic	
Epidemic Routing [4]			•		Random
Two-Hop forwarding [5]			•		Random
(p,q)-Epidemic Routing [6]			•		Random
Spray and Wait [7]			•		Random
Spraying [8]			•		Random

Infostation[9]	•		•		Random
SWIM [10]	•		•		Random
Data MULEs [11]		•	•		Random
ZebraNet [12]		•	•		History
MV Routing [14]			•		History
PROPHET [15]			•		History
CAR [16]			•		History
SCAR [17]			•		History
MobySpace [18]			•		History
STR [19]			•		History
Message Ferrying [22]		•	•		Movement control
Inter-Regional Messengers [23]		•	•		Movement control
HoP-DTN [25]		•	•		Movement control
Erasure Coding [26]			•		Coding
Network Coding [29]			•		Coding
SPST [30]				•	Shortest path
Knowledge Oracles [31]				•	Shortest path

Table 2-2 presents a brief comparison of some of the most important characteristics of these protocols. The complexity and suitability levels are, of course, subjective.

TABLE 2-2: COMPARISON OF EXISTING ROUTING APPROACHES

Approach	Directed	Information (1)	Complexity (2)	Suitability (3)	Publication
Epidemic Routing [4]		-	•	•••	2000
Two-Hop forwarding [5]		-	•	••	2002
(p,q)-Epidemic Routing [6]		-	•	•••	2008
Spray and Wait [7]		-	•	•••	2005
Spraying [8]	•	L	••	•	2001
Infostation[9]		-	•	••	1997
SWIM [10]		-	•	•••	2003
Data MULEs [11]		-	•	•••	2003
ZebraNet [12]	•	C	•	•••	2004

MV Routing [14]	•	C, L	••	•	2005
PROPHET [15]	•	C	••	••	2003
CAR [16]	•	C, F, T	•••	•	2005
SCAR [17]	•	C, F, T	••	•••	2007
MobySpace [18]	•	F	•••	••	2005
STR [19]	•	C, T	••	••	2003
Message Ferrying [22]	•	L	••	••	2004
Inter-Regional Messengers [23]	•	B, L	••	•	2006
HoP-DTN [25]	•	L	••	•	2007
Erasure Coding [26]		-	•••	••	2005
Network Coding [29]		-	•••	••	2005
SPST [30]	•	C, T	•••	•	2004
Knowledge Oracles [31]	•	C, B, O, T	•••	•	2004

(1) Information used: B = buffer occupation; C = contacts; F = flexible or application dependant; L = location; O = other; T = time.

(2) Conceptual and implementation complexity: • = easy to understand and implement; •• = somewhat complex, conceptually more complicated and/or requires information or functionalities not readily available; ••• = complex algorithm, hard to understand and/or to implement.

(3) Suitability for use in WSNs: • = not designed for WSNs nor easily adaptable; •• = not designed for WSNs but adaptable, designed for WSNs but using unrealistic assumptions, or conceptually adequate but not sufficiently detailed; ••• = designed for WSNs, fully adequate.

2.4 Discussion

This chapter listed many approaches that, even when not designed with WSNs in mind, may still have some degree of applicability. Looking at Table 2-1, one can see that most approaches assume a stochastic network evolution (there is no concrete knowledge of future network topology) and the absence of network infrastructure (every node is seen as equal by the routing algorithm).

The former assumption is easy to understand, as there are few real-world cases of deterministic opportunistic WSNs (one being, for instance, a rail transport network with pre-defined static train schedules). The latter assumption is more debatable, but there are some reasons why it is made. First, it is important to note that approaches that were not specifically thought for use in WSNs may rely on scenarios in which network homogeneity is standard, such as pure mobile ad-hoc networks (MANET) – one example being Two-Hop Routing [4]. On the other hand, an opportunistic WSN will normally (but not always) have a fixed component, frequently featuring static sensor nodes, mobile carrier nodes, and fixed sinks. The existence of sink nodes is assumed in most WSNs, and is not enough to classify a network as having infrastructure. There are also fully mobile networks: ZebraNet [12], for instance, only uses mobile sensor nodes and a mobile sink node.

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 [4] and the ZebraNet history-based algorithm [12], which are also two of the simplest. This should come as no surprise given that, by increasing routing complexity and/or 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 become too complex for any real scenario.

3 Target Scenario and Network Architecture

There are uncountable different WSN usage scenarios. As previously stated, it is very hard, if not impossible, to develop a true general-purpose solution. To be realistic, a sensible set of restrictions must be specified. Architectural aspects of the network are tightly coupled to these restrictions, hence they are jointly described.

Sparse networks, those with low node density, are the most challenging from an OR point of view, since decisions carry a graver impact on global performance. They are also the ones most in need of OR solutions, as high-density networks can in most cases make use of other approaches, namely traditional ad-hoc routing. Networks are also assumed to be highly scattered, with permanently-connected partitions being a rare occurrence. This negates the need for hybrid routing protocols, which include a separate, non-opportunistic mechanism for routing inside these partitions.

Highly mobile networks, in which the majority of nodes (or, in the limiting case, all of them) move, also make for a more interesting case, as mostly static networks are easily served by a MULE-like architecture [11]. Passive mobility is another reasonable assumption. Even though there are cases in which it makes sense to have on-demand mobile agents, these constitute a minority due to cost and complexity. Networks with deterministic evolution are seldom found and well served by existing solutions, so it makes sense to focus on those with stochastic evolution. That does not imply, however, the total absence of movement patterns on the network: if that were the case, no routing algorithm would do better than a random forwarding approach. Consequences of high-speed movement, found in scenarios such as motorways and railway networks, are outside the scope of this work.

For realism's sake, resource constraints must also be taken into account. While sensor nodes are becoming more powerful each day, they will keep on being a heavily-constrained system in the foreseeable future. Radio range and bitrate, processor speed, memory capacity and energy are examples of scarce resources. Energy limitations are perhaps the most serious: the reduced size and cost of nodes prevent the use of long-life batteries, and while there are energy-harvesting solutions, these too are expensive, inefficient or impractical.

Finally, in most 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 single-tree *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, the focus has been placed on low-density, highly mobile networks with stochastic evolution and convergecast architecture, 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.

3.1 Example scenario – Organic Silvopastoral Systems

Organic farming is assuming an increasing importance all over Europe due to its perceived higher product quality, possible health benefits and reduced environmental impact. It is based on the use of natural processes and subject to hard, government regulated constraints on the use of chemical helpers such as synthetic fertilisers and pesticides. Animals grown under organic farming regimes are also subject to the same constraints, and must generally be fed with natural products, these too coming from organic farms.

These requirements create an incentive for the use of a holistic model, taking advantage of synergies between both practices: free-grazing livestock (most commonly sheep, goats, cattle, pigs and horses) provide fertilization, control the proliferation of invasive plants and reduce fire hazard, while at the same time naturally feeding and using the trees for shelter.

Traditional silvopastoral systems are abundant all over the world. In the Portuguese case, the main ones are plantations of Cork Oak (the *montado*), Pyrenean Oak, Chestnut and Olive Tree orchards, with the last maybe being “the most complete multipurpose form of land use in the world” [32]. While the industrial high-yield agriculture trends of the last decades have threatened these systems, the new trend towards organic farming (and the high economic value of organic olive oil) is thought to open the gates for its survival and expansion.

There is presently interest in using WSNs for monitoring several cultures, seeing as they present undeniable advantages, but most proposed systems assume some form of long-range communication, typically public cellular networks. Even though there is also some research on livestock monitoring WSNs, no project combines both.

The use of an opportunistic WSN integrating both tree-mounted sensor nodes and livestock carried sensor nodes would allow monitoring of the whole system, and using the animals as information carriers would drop the dependency on external communication systems and its associated costs. Several solar-powered sinks could be deployed on sites the animals are known to frequently visit, and relay data via a long-range radio link.

An example of such an application can be seen in Figure 3-1, where sheep help carry a message from a tree-mounted node, through other mobile and static nodes, ending with delivery to a sink node.

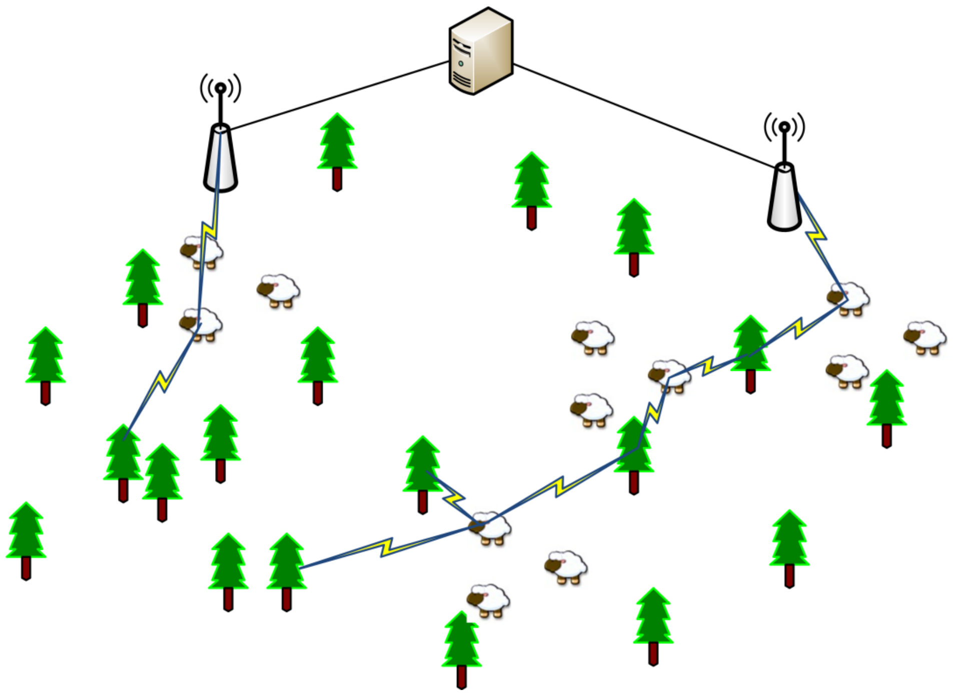


FIGURE 3-1: EXAMPLE OF A SILVOPASTORAL SYSTEM SCENARIO

4 CHARON Design

In this chapter the main considerations behind CHARON's design will be discussed. The initial design goals will be listed, followed by a brief overview of the approach, a detailed description of the mechanisms used, and the reasons leading to their selection.

4.1 Design Goals

Considering the target scenario, four main goals were defined for the development of CHARON: reliability, simplicity, efficiency and flexibility. Some of these goals are in conflict with each other, e.g., increasing reliability may require a less efficient solution. In the course of the design phase, choices had to be made to achieve a balanced solution.

Reliability. This is the basic goal of any routing solution, and the single goal of many. It can be defined as the delivery the largest possible fraction of messages, in a limited time frame, while they are still useful for the application. Note that, beyond guaranteeing a message arrives within its usefulness window, minimizing delivery delay isn't necessarily a concern.

Simplicity. Simplicity in this context comprises not only computational simplicity, but also that of the implementation. Computational simplicity is necessary because the available hardware has severe resource constraints. Even if resources suffice to run somewhat complex routing protocols, the network's objective is not to route messages but to run an application, and the bulk of resources should be left for the application to use. A solution is of limited usefulness if it is hard to implement or deploy, and so the developed solution should be easily implemented in any platform. For the same reason, dependencies on hardware that is not normally available must also be avoided.

Efficiency. The least possible amount of resources should be required to execute the required tasks. That includes using less memory, transmitting fewer messages and spending less energy. By minimizing the number of transmissions, memory requirements are usually reduced, and in some cases energy can also be saved[2]. Energy-efficiency does nonetheless require additional thought, and frequently involves specific power management mechanisms.

Flexibility. The developed solution should be usable in many settings, provided these settings fit the target scenario. To accomplish this goal, design has to be done with (relative)

[2] Some radios use more energy while idle listening than while transmitting. In those radios, reducing the number of transmissions has no direct impact on energy usage. Nevertheless, by transmitting less messages, the radio rests unused for longer periods, and can be turned off.

generality in mind, right from the start. Nevertheless, all applications have specificities, and the system must be easy to customize to each specific setting. Finally, there is the question of intra-scenario flexibility: even in the same network there may be different requirements for different data. The solution should be able to accommodate all these requirements.

4.2 Solution Overview

CHARON 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 [33]. 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. The decision to use this metric, versus, for instance, the nodes' relative mobility or sink encounter frequency, was made in an effort to align the mechanism to the goal, which is to get the data to the sinks before it expires (see Section 4.3).

Nonetheless, optimizing delay isn't the only concern, as limited network resources should 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 (see Section 4.3.2).

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 (Figure 4-1).

```
// 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
```

FIGURE 4-1: FORWARDING DECISION ALGORITHM

Messages are basically forwarded using a single-copy approach, meaning that there is but one 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 doesn't allow forwarding except in the case that the node meets a sink. Messages in this state are known as *zombies*, and the strategy was named *hybrid replication*. The traditional multi-copy paradigm is also supported for situations that require it (see Section 4.3.3).

In order to realize the intra-scenario 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 (see Section 4.3.4).

As minimizing the number of transmissions isn't enough to provide an energy-efficient solution, CHARON has built-in support for synchronous radio power management, significantly reducing energy waste (see Section 4.3.5). 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 reference and the reference age (see Section 4.3.6).

CHARON operates as a bundle layer, being implemented on top of the 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 trade-off. 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. Through the entire document, the terms message and bundle are used interchangeably, unless otherwise noted (see Section 4.4).

4.3 Feature Design

4.3.1 Delay-Based Routing

The main goal 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:

- 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.
- 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 ($edd : V_c \rightarrow \mathcal{R}^+$) and the ICT ($ict : V, V_v \rightarrow \mathcal{R}^+$) between both nodes (1).

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

In fact, ICT describes 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 reduced.

A node's EDD is equal to the minimum achievable delay, or the delay through the quickest known node, given by (2).

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

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.

A problem with this approach is that ICTs don't degrade naturally, that is, if two nodes ($a, b, \subset V$) don't meet, their ICT value stays unchanged. This may have serious consequences if b is a's best known forwarder, and b stops being a good forwarder, perhaps because its movement pattern changed or simply because it ran out of energy. As a's EDD also remain unchanged, it is advertising itself to be a better forwarder than it really is, potentially degrading the entire network's performance. Possible fixes include setting a threshold on the maximum allowable ICT overrun time (after which the entry is deleted), periodically aging the ICT values or taking this difference into account. The last course of action was preferred, replacing eq. (1) with (3).

$$d(v,c) = edd(c) + ict(v,c) + ictVar(v,c)\, H\big(ictVar(v,c)\big), c \in V_v \tag{3}$$

$$ictVar(v,c) = \big(time - lastContact(v,c)\big) - ict(v,c) \tag{4}$$

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 added.

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.

4.3.1.1 EDD Calculation as a Shortest-Path Problem

On a network-wide level, computing each node's EDD can be seen as a shortest-path problem. Formally, the problem can be defined as follows: given a directed graph $G = (V, E)$ with a weight function $w : E \rightarrow \mathcal{R}^+$, the weight of a path $p = \{v_0, v_1, \ldots, v_k\}$ is given by (5).

$$w(p) = \sum_{i=1}^{k} w(v_{i-1}, v_i) \tag{5}$$

Defining a set $S \subset V$ containing all the sink nodes and taking the edge's weights to be their ICT value, the EDD (δ) of a node $u \in V$ is equal to the shortest-path weight to any member of S (6).

$$\delta(u) = \begin{cases} \min\left\{w(p): u \overset{p}{\rightarrow} v\right\}, \exists\, u \overset{p}{\rightarrow} v, \forall\, v \in S \\ \infty\,, \nexists\, u \overset{p}{\rightarrow} v, \forall\, v \in S \end{cases} \tag{6}$$

In Figure 4-2, a progressive view of the operation is shown. In (A), a weighted, non-directed graph is presented, where each edge is marked with the measured ICT between the nodes it connects. As all sinks are logically equivalent, they can be reduced to a single virtual sink, thereby reducing the problem to the single-destination kind. Then, in (B) the paths with the lowest cost (represented in bold and with directional arrows) are selected and their weight used to establish each node's EDD (the number in the centre). In the resulting graph (C), all paths but the used ones have been omitted, resulting in a shortest-path tree.

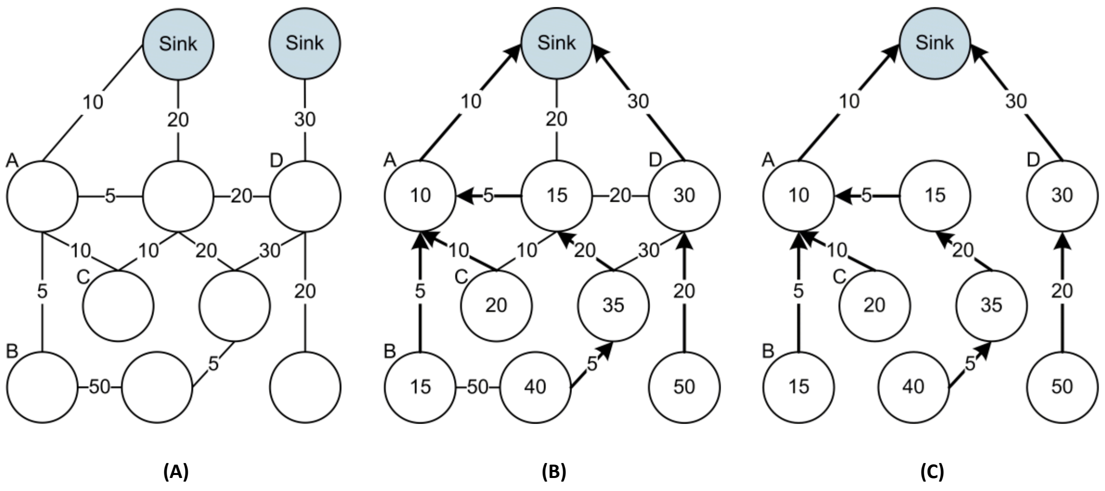


FIGURE 4-2: EDD COMPUTATION AS A SHORTEST-PATH PROBLEM

In reality, however, the calculation is done in a distributed way, with incomplete and outdated information. Each node determines its own EDD, based only on its known nodes, their last-received EDD and the recorded ICT, having no knowledge of the remaining tree. Accordingly, the resulting solution may not be the best in all cases. It should also be noted that, despite this method being used to compute nodes' EDDs, messages aren't necessarily routed along the shortest-path tree. A node may forward a message to any node it meets with better EDD and global score, regardless of it being the estimated best forwarder (shortest path).

4.3.2 Multivariate Utility Function

The concept of multi-factor utility functions has been used before in OR protocols (e.g. [17]). The general idea behind its use is that it is possible to get a better solution by taking more information into account, which is commonly 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, lower pressure may be a good indicator.

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 the most commonly available data, is (7).

$$S(v) = -edd(v) + batteryLevel(v) + freeBuffer(v) \tag{7}$$

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 (7), 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.

4.3.3 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 can be 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.

The single-copy strategy is normally more efficient, as it does lead to lower buffer occupation and also to a lower number of message transmissions. It does however have some important disadvantages: when a suboptimal routing decision is made, it tends to have direr consequences, as there are no alternate paths being concurrently attempted. It is also possible that the node carrying the single copy fails, eliminating it permanently. These limitations lead to lower delivery rates and higher average latency.

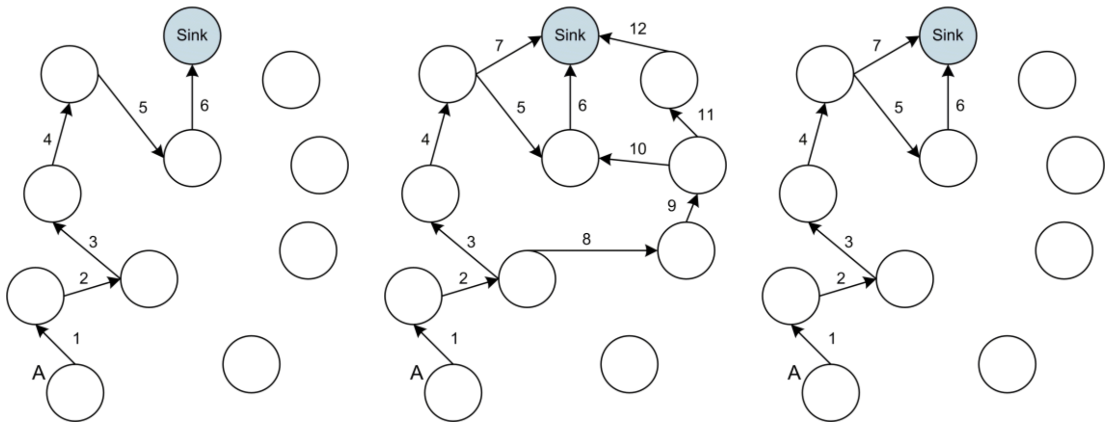
The multi-copy strategy has the opposite problem. Delivery rates and latency are usually better, but are tied to higher overheads, in the sense that there are more transmissions per message, also leading to higher energy waste. In addition, this solution behaves badly under high loads, as the extra copies are likely to exhaust the available buffer, resulting in dropped messages and severely degrading network performance. The number of replications and the circumstances in which they are made can be constrained, mitigating this problem, at the cost of performance under low loads.

Having high efficiency as a goal, a mostly single-copy approach was chosen, with a single 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*. The solution becomes a *hybrid* strategy, combining all the advantages of single-copy schemes with some of the performance improvements made possible by multi-copy ones.

Zombies are leftover copies from previously carried messages that 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. A small comparison of the three strategies can be seen in Figure 4-3:

- 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.
- 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.
- 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 also

possible that a zombie copy reaches the sink before the current holder of the message, in which case delivery latency is reduced.



(A) (B) (C)

FIGURE 4-3: DIFFERENT REPLICATION STRATEGIES (SINGLE COPY, MULTI-COPY AND HYBRID)

Zombies have negligible impact on the routing efficiency (adding at most a single transmission per message), yet share the same properties of message copies in that they increase fault tolerance and improve delivery statistics. It is also necessary to examine the subject of buffer use, and to explain why this strategy fares better than multi-copy in that regard. A zombie message, being a complete copy of its parent message, naturally requires the same buffer space. The fundamental difference is easily understood when a node runs out of memory:

- 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 won't delete the same message, making it undeliverable.
- 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 has to be minimized at any cost. The system supports a secondary purely multi-copy mode for use in such situations. In this mode CHARON does not tag forwarded messages as zombies, continuing to forward them as before. This is clearly wasteful, as a message can be forwarded to a node that is already carrying it, but unavoidable without introducing additional message types or additional beacon fields. Given that this mode is meant to be seldom used, the introduction of additional complex mechanisms has been avoided. A node can however keep track of other nodes to which it has already forwarded each message and refrain from forwarding to them again. 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.

4.3.4 Quality of Service

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.

Before going into details, it is important to clarify 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 put into practice in the target scenario and within the stated goals, and as such weren’t 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:

- Utility function
- Replication strategy
- Time to Live (TTL) value

Depending on the chosen settings, the result can range from purely delay-based, multi-copy 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:

- A low-priority class used for bulk monitoring data, configured with an energy-aware utility function and hybrid replication
- A high-priority class used for urgent alarm data, configured with no utility function and multi-copy replication

An example of such an arrangement is presented in Table 4-1, 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.

TABLE 4-1: EXAMPLE CLASS CONFIGURATION

Class	Utility function	Replication strategy	TTL value
Monitoring	$S(c) = -edd(c) + freeBuffer(c) + batteryLevel(c)$	Hybrid	72 h
Alarm	$S(c) = 0$	Multi-copy	12 h

Using this simple scheme, CHARON is able to provide multi-copy-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. It must be emphasised that this is only true if alarm messages account for a small fraction of the total as otherwise global performance will be severely degraded.

4.3.5 Power Management

Regardless of how high an algorithm's routing efficiency is, it can't 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 [34] and asynchronous [35] [36] cycling, as well as more advanced, on-demand solutions such as wake-up radios [37]. Asynchronous cycling presents a sub-optimal 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 seems 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 CHARON allows applications to listen 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 using a simple formula (8).

$$\tau = (time \setminus roundPeriod + 1) * roundPeriod \tag{8}$$

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. It is expected that in most scenarios radios can be turned on for a few seconds every minute, leading to duty cycles around 10%. Only under optimal conditions can the duty cycle go lower than 1%. Once again, there is a balance to be struck between energy efficiency and network performance.

When a node does not yet have a time reference available, synchronized radio cycling is impossible. It was decided that a fall-back mode not be implemented, 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.

4.3.6 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, it was decided to use a synchronization protocol.

There are already several high-precision time synchronization protocols designed for WSNs [38]. 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 can be used. The (very 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 Figure 4-4.

```
algorithm update_time (c) is
    if localTimeAge ≥ timeAge(c) + stepPenalty then
        localTime ← time(c)
        localTimeAge ← timeAge(c) + stepPenalty
    end
end
```

FIGURE 4-4: TIME SYNCHRONIZATION ALGORITHM

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.

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. It can also be queried and used directly by applications.

4.4 Messages Formats

Nodes detect each other, and routing information is exchanged by periodically broadcasting beacons. Beacons contain the needed data for all parts of the solution to operate. The structure of a beacon is shown in Figure 4-5.

Time Reference	Time Reference Age	
EDD	Available Memory	Available Power

FIGURE 4-5: STRUCTURE OF A BEACON MESSAGE

Note that the format isn't completely specified, as the size of each field is implementation-dependent in order not to limit efficiency or applicability. Useful time values are required to have reasonable precision, and are likely to require larger sizes than memory or power indicators. Also note the lack of a source identifier: that is handled at the lower layers, and there is no need for duplication.

Messages are transferred using unicast connections. The structure of a data message is shown in Figure 4-6.

Source Address	Sequence Number	
Timestamp	Traffic Class	Data Stream
Data (...)		

FIGURE 4-6: STRUCTURE OF A DATA MESSAGE

All fields are immutable, i.e., are never changed by carrier nodes. The sequence number is a monotonically increasing integer and should be dimensioned so that it does not roll over during the network lifetime – even at a high generation frequency of 1 message per second an unsigned 32-bit integer should be enough for over 130 years. The timestamp is used in prioritizing messages for transmission, as well as checking for TTL expiration. The traffic class is used for QoS purposes, as previously explained, and the data stream identifier is present so that sinks can separately queue messages for concurrent applications. No limit is imposed as to how much data a message can carry but, as bundle-layer fragmentation is not supported, that amount is limited by the maximum allowable payload size of the underlying layer.

There are no other routing-specific messages, in an effort to maintain the approach’s simplicity. This also means there are no bundle-layer acknowledgements; it is a non-conversational protocol. Data loss is prevented by relying on lower-layer acknowledgements.

5 Reference Implementation

A reference implementation of CHARON was developed, primarily as a proof of concept. It is meant to allow validation and evaluation of the proposed solution in a real setting. It also helped to better assess the difficulty of implementing CHARON in real WSN hardware. This chapter describes the implementation's architecture.

5.1 Development Platform

Most previous [39] [34] and ongoing WSN experiments at GEMS[3] have used Crossbow MICAz nodes [40] and the TinyOS operating system [41]. Despite this being a somewhat flexible combination, developing for it can be tiresome, and it is also an aging platform with severe resource limitations (although successors are available).

For CHARON's reference implementation, it was decided that Sun Microsystems' Small Programmable Object Technology (SPOT) [42] should be used. The SPOT is the result of a project started at Sun Labs in 2004, and presents several important advantages when compared to the aforementioned platform. This implementation also presented an opportunity to test a new platform for future projects at GEMS.

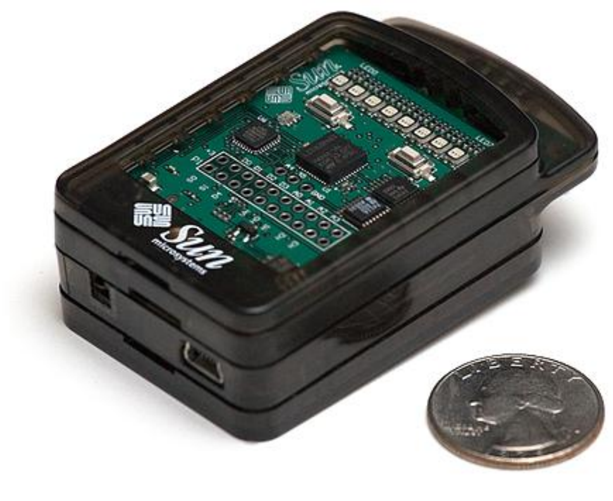


FIGURE 5-1: SUN SPOT NODE (IMAGE CREDIT: SUN MICROSYSTEMS)

The SPOT (Figure 5-1) is a fairly powerful system, based on the following hardware:

- 180-MHz 32-bit ARM9 processor
- 512KB of RAM

[3] The Group of Embedded Networked Systems and Heterogeneous Networks at LEMe/IST

- 4MB of Flash memory
- IEEE 802.15.4-compliant [43] CC2420 radio transceiver [44]
- 3.7v, 750mAh rechargeable lithium-ion battery

It also comes with a sensor board featuring:

- A 3-axis accelerometer
- A temperature sensor
- A light sensor
- 8 RGB LEDs
- 2 Switches
- Analogue and digital input and output pins

SPOT nodes are programmed using Java. They do not run an operating system, replacing it with a bare-metal Java Virtual Machine (VM), Squawk [45]. Squawk is a very lightweight VM, it too mostly written in Java, and targets small, resource constrained devices, such as WSN nodes. It is compliant with the Java Micro Edition (ME) Connected Limited Device Configuration (CLDC), version 1.1. It provides a full-featured Java environment, with support for multiple threads, application isolation, dynamic loading and linking, and exact garbage collection. Squawk's implementation on the SPOT is bundled with specific libraries that facilitate development for the platform, e.g., by allowing easy access to the sensors and other connected hardware. It also includes a full communication framework that provides low-level radio access, high-level connection-oriented and connectionless protocols, as well as mesh routing protocols.

One of the advantages to using SPOTs is that they are relatively well equipped, being close to the current state of the art of WSN hardware. However, the single most important argument going for them is the fact that they are Java-based, making development much easier for non-expert users. They also benefit from an entirely open-source approach to both software and hardware development. SPOTs have been previously used in WSN contexts, such as KTH's AquaWSN [46] and WaterWell [47] water quality monitoring projects.

5.2 Architecture

CHARON is implemented as a library that can be included in any application. It follows an object-oriented approach with several high-level logical blocks, each typically composed of several classes. Figure 5-2 shows a logical overview of the reference implementation, in which blocks are matched to the system's main features.

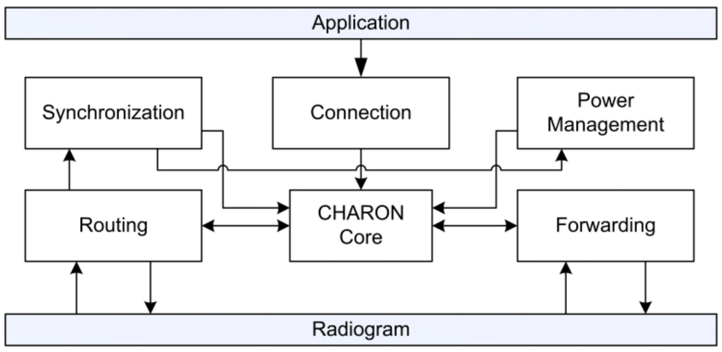


FIGURE 5-2: LOGICAL OVERVIEW OF THE IMPLEMENTATION

The blocks with coloured backgrounds represent the layers above (`Application`) and below (`Radiogram`). Each block in between them is part of CHARON, and will be described in the following sections. Blocks are not entirely separate, and some components may be part of more than one, so the previous figure should be understood as a simplification. While an effort has been made to apply the Object-Oriented Programming (OOP) principles of modularity, isolation and abstraction to their full extent, in some places it wasn't reasonable to do so, mainly for performance reasons.

5.2.1 Routing

The most important components of the routing block (Figure 5-3) are the routing engine (`RoutingEngine`), the beacon sending (`BeaconThread`) and receiving (`ListenThread`) threads, and the routing table (`RoutingTable`).

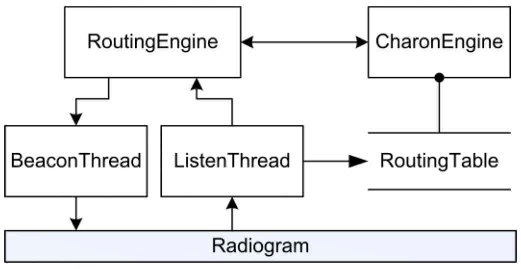


FIGURE 5-3: COMPONENT DIAGRAM FOR THE ROUTING BLOCK

The `RoutingEngine` module is, as expected, the main module in the block. In addition to coordinating the other modules, it keeps track of all contacts, storing for each known node its ICT and EDD values. It also processes received beacons and updates the routing table.

Each QoS class has specific routing logic that must be considered by RoutingEngine and other system components. To do so, classes are described by objects implementing the ServiceClass interface, and registered with a static manager, omitted from the figure for clarity. This interface contains methods to access each of the class-specific parameters, and to calculate a node's score according to the class's utility function. For simplicity reasons, zombies are also considered a traffic class.

The routing table has a single entry for each class, indicating the next hop. It is located outside the RoutingEngine to facilitate access to the forwarding block. It is protected by a *wait/notify* mechanism that allows the interested threads to synchronize: when an entry is edited, the waiting threads are notified.

BeaconThread and ListenThread have simple assignments: the former grabs the necessary information from the system and uses it to broadcast beacons, the latter receives beacons broadcast by other nodes and passes them on to RoutingEngine and other interested modules. This use of independent threads with self-contained functions considerably simplifies the system, reducing the need for centralized control or state sharing.

5.2.2 Forwarding

The main components in the forwarding block are the forwarding engine (ForwardingEngine), the message sending (ClientThread) and receiving (ServerThread) threads and the routing table (RoutingTable), presented in Figure 5-4. The buffer is, of course, used to store the messages being carried.

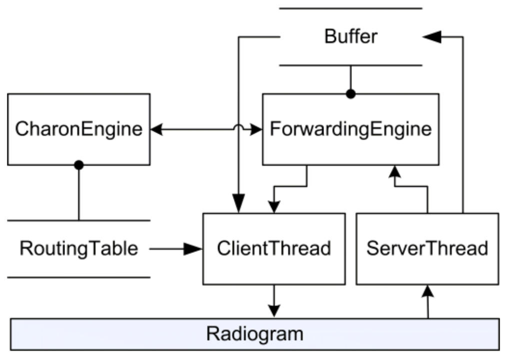


FIGURE 5-4: COMPONENT DIAGRAM FOR THE FORWARDING BLOCK

The buffer is implemented as a set of several linked lists, one per class. These lists are kept sorted by message timestamp, so that older messages are forwarded first. Entries are sorted on insertion, trading upfront cost for savings in every dispatching access. The buffer has a size limit, defined as a number of messages, which is freely distributed among classes. In order to reduce the load on the garbage collector, all the list nodes are created on start-up and kept in a shared pool[4]. Cleanups are periodically executed to remove expired messages and, if buffer space goes under a specified limit, zombies (which are non-critical) are deleted to make room for other messages.

`ServerThread` continuously waits for messages to be received and adds them to the buffer, while `ClientThread` blocks on `RoutingTable`'s wait/notify mechanism. When the table is updated, the thread wakes up and matches available routes to available queues, starting with the highest priority class[5]. As soon as it finds a route for which there are messages to send, it begins transmission. When all messages in that class have been forwarded, it moves to the next class. This means, in effect, that while high-priority messages are queued and a suitable round is available, lower-priority classes are not served. Starvation of low-priority queues is possible if many high-priority classes are carried, but the system has not been designed for such usage patterns. If a transmission fails, the message is put back into the buffer. If a message's class uses zombies, the message is moved to the zombie queue after being sent. The thread performs a short sleep between each transmission as a way to throttle resource and bandwidth occupation and allow more critical functions to execute. For instance, by imposing non-transmission periods, channel access contention is reduced and beacon messages suffer lower contention delays, improving synchronization precision.

In case the buffer fills up, message reception must be halted. That only takes place when the node broadcasts the following beacon, advertising the lack of available memory. However, before that occurs, messages may still be forwarded by other nodes. The obvious solution would be to close the listening connection, resulting in acknowledgements not being sent, and causing the sending nodes to stop. However, an optimization on the lower levels of the SPOT stack leads to closed connections still acknowledging received messages, forestalling this approach. This problem was solved by attaching the free buffer space to each routing entry. This value is decremented by the node every time a message is sent. Because there may be other nodes transmitting to the same destination, the announced buffer space should not be

[4] In the absence of the shared pool, new list objects be would be allocated every time a message was received, requiring the garbage collector to remove these objects when the message was later forwarded, and wasting CPU cycles.

[5] The concept of class priority wasn't previously discussed as it is implementation-specific and not a design choice. Each class is assigned an integer that defines the order in which it is served. Urgent data should be configured with the highest priority level, while zombies should receive the lowest.

the real one, but a fraction of it. The division factor is scenario-specific, and should be set with respect to the number of nodes expected to simultaneously transmit to a single one. On most cases it is unlikely to have a significant effect on network performance, only reducing the maximum number of messages forwarded between beacons. In the worst-case scenario, in which the division factor is set too low and many nodes happen to transmit a large number of messages to the same destination simultaneously, some messages might be silently dropped for lack of buffer space. This is clearly undesirable, so it is best to always choose a factor higher than the expected.

5.2.3 Time Synchronization

The time synchronization subsystem is very simple, and composed mainly of the `TimeKeeper` module (Figure 5-5). It uses the same threads of the routing block to get information in and out of the beacons.

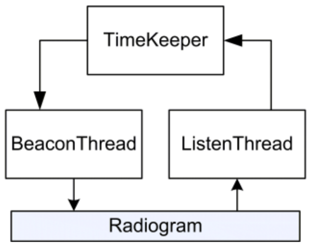


FIGURE 5-5: COMPONENT DIAGRAM FOR THE TIME SYNCHRONIZATION BLOCK

`TimeKeeper` manages all the time information. It keeps global time and provides access and update methods. Three values are stored:

- The delta (Δ) between local and global times
- The reference age at the time it was received
- The local time at which the clock was synchronized

Using these values, the module converts between local and global times. The function that converts global to local times is (9), whereas the converse operation inverts the delta's sign.

$$global2local(t) = t + \Delta \qquad (9)$$

When a beacon is received by `ListenThread`, and even before it is passed on to the routing engine, the time information is sent to `TimeKeeper`. If it is more recent than the current reference, the latter is replaced. `BeaconThread` grabs the current time values and writes them to the beacon just prior to dispatching. Both threads use the highest priority level, in order to minimize synchronization error.

5.2.4 Power Management

When a time reference is available, the system can commence round generation. That is done by the power management block which, besides `RoundGenerator`, only uses components belonging to other subsystems – it is tightly integrated with the system. An overview of the components involved can be seen in Figure 5-6.

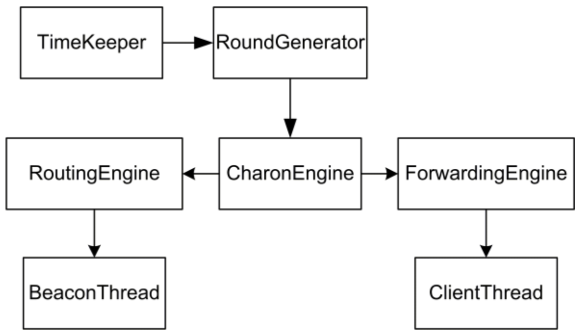


FIGURE 5-6: COMPONENT DIAGRAM FOR THE POWER MANAGEMENT BLOCK

`RoundGenerator` uses a Java Timer to schedule tasks. At the beginning, a control task (`ControlTask`) is scheduled periodically to wait for the time reference. When one is found, the control task determines the global time when the next round should start – as specified in Section 4.3.6 –, converts it to a local time, and schedules a `RoundStartTask` for execution. This task turns the radio on and resumes system activity, in addition to scheduling the following round.

An end-of-round task (`RoundStopTask`) is also scheduled: it not only turns the radio off but also invokes the garbage collector at a time the system is still on but unlikely to be active – the client application is not controlled by CHARON and may be running. This task notifies `CharonEngine`, which requests for the radio to be shut down, and calls a *pause* method on the other engine objects. This method stops all activity of the sending threads; receiving threads don't need to be suspended, as they will be blocked while the radio is off.

The SPOT's power management library automatically throws the system into deep sleep mode – a very low power state – when all threads are blocked and the radio is off. As long as the application is also inactive, that means CHARON's radio power management solution is, in fact, extended to the entire system.

5.2.5 Network Connections

This implementation of CHARON uses *Radiogram* as the underlying connection protocol. Radiogram is a lightweight connectionless protocol. It is a generally unreliable protocol, but in the single-hop case it guarantees that messages will not be silently lost (with the exception pointed out on Section 5.2.2) or delivered out of sequence, though they can be delivered more than once. It relies on 802.15.4 acknowledgments to guarantee delivery.

Communication is accomplished using a socket-like model. In each node CHARON operates four connections:

- A broadcast sending connection, on the beacon port, for `BeaconThread`
- A listening connection, on the beacon port, for `ListenThread`
- A unicast sending connection, on the data port, for `ClientThread`
- A listening connection, on the data port, for `ServerThread`

`ClientThread`'s connection is the only non-permanent one, being created each time a node is about to start forwarding messages.

Since the Java CLDC does not support object serialization, a message marshalling[6] mechanism had to be created. Both bundles and beacons extend the *Message* class and can be easily marshalled into a radiogram's payload or unmarshalled out of it.

5.3 Application Interface

Having a simple interface is a critical part of CHARON's developer-friendliness. Its basic interface solution consists of just one class, `CharonConnection`. That is the only required interaction between an application and the system. Access to `TimeKeeper` and `RoundGenerator` is also possible, but entirely optional. Figure 5-7 illustrates the possible data flows.

[6] Marshalling is the process of transforming the memory representation of an object to a format suitable for transmission or storage.

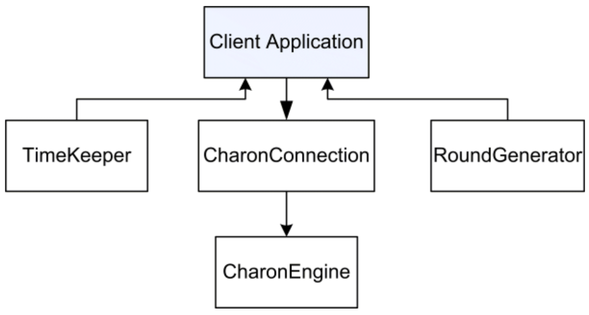
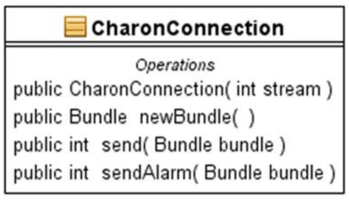


FIGURE 5-7: APPLICATIONS' INTERACTION WITH CHARON

The data message class (`Bundle`) implements the standard datagram interface used by the built-in high-level protocols, requiring minimal changes to existing application. In particular, it supports typical Java data input and output streams, allowing its payload to be written and read using simple operations.

An instance of `CharonConnection` (Figure 5-8) is created for each data stream an application wishes to use. A connection provides methods for instantiating bundles and sending them. Two sending methods are available and they differ only in the service class assigned to the message. This structure was thought to be easier to use considering there are only two classes. If more service classes were configured, the interface could instead be adapted to receive the class ID as either a parameter to the constructor or to the send method. The standard CLDC Generic Connection Framework (GCF) was not used as it would introduce unneeded complexity.



```
public CharonConnection( int stream )
public Bundle  newBundle(  )
public int  send( Bundle bundle )
public int  sendAlarm( Bundle bundle )
```

FIGURE 5-8: CONNECTION INTERFACE

Both `TimeKeeper` and `RoundGenerator` are system-wide static classes, and their abridged interfaces can be seen in Figure 5-9. `TimeKeeper` provides access to the current global time and converts between local and global times. `RoundGenerator` allows the application to subscribe to notifications of synchronous rounds by using a simplified Observer design pattern. Any class wishing to be notified must only implement the `RoundObserver` interface and call the `RoundGenerator.attach` method.

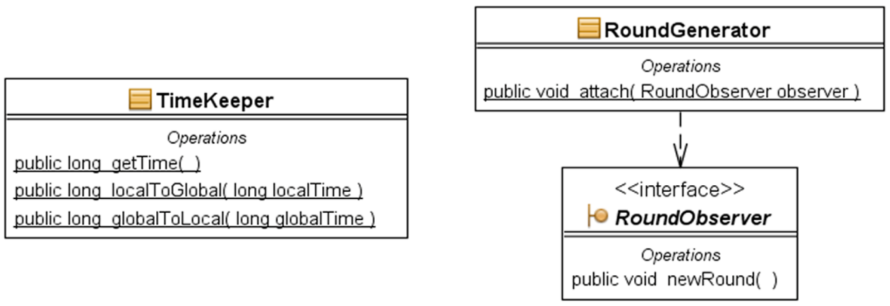

TimeKeeper
Operations
public long getTime( )
public long localToGlobal(long localTime)
public long globalToLocal(long globalTime)
RoundGenerator
Operations
public void attach(RoundObserver observer)
<<interface>>
RoundObserver
Operations
public void newRound( )

FIGURE 5-9: TIME AND ROUND INTERFACES

5.4 Sink Library

The previous sections described the node-deployed part of CHARON. There is a sink (or host) library too, running on the computer connected to the SPOT base station. The sink has to broadcast beacons, like any other node, and receive messages. Both mechanisms are similar to the ones used in the node library, and will not be described in detail.

Received messages, instead of being put into a class-specific queue, are instead grouped according to their stream ID. Given that the system deals with delay-tolerant data, applications must be prepared to handle out-of-order data, and as such there is no reason to reorder messages. The system does, however, keep track of the already received messages and drops any duplicates, although this behaviour can be disabled if necessary.

To receive messages, applications must first instantiate a `CharonConnection` object (Figure 5-10) with the desired stream ID. The sole method provided by the connection (`receive`) goes into a blocking wait until a message is available, at which time it returns.

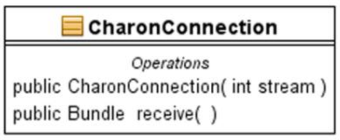


FIGURE 5-10: HOST INTERFACE

The host library does not currently include support for multi-sink data aggregation, as this is outside the scope of the project. Such support can easily be implemented at the library or application levels by re-marshalling (using the built-in marshalling methods) and sending the received bundles over an IP connection.

5.5 Implementation Complexity

One of the goals set for CHARON was its ease of implementation, and verifying it was also one of the reasons leading to the development of this prototype. While ease of implementation is always a topic of subjective evaluation, some objective metrics can be presented.

The full implementation contains 32 classes and 1517 physical source lines of code (SLOC), excluding utilities and debugging functionality. It was finished in one and a half months of part-time work by a developer unfamiliar with the platform, while an experienced full-time developer could probably have done it in less than two weeks. These development times appear to be acceptable, considering the multiple problems CHARON solves.

Although very subjective, a short comparison can be made with TinyOS, considering the implementation of a power management solution similar to the one used (although more complex) by the same developer [34]. That implementation required more than one month of work, in addition to an intermediate redesign, mainly because of the unfriendly and exotic nature of the development environment.

The full compiled suite stands at 47 KB, a value that must be seen in the context of the used framework and system. In effect, given that the system has 4 MB of available Flash memory, CHARON's footprint isn't relevant. Unfortunately, runtime RAM and CPU usage could not be quantified, as support for profiling is not yet implemented in the SPOT firmware.

6 Evaluation

In order to validate the ideas behind CHARON, and evaluate its performance, a set of evaluation experiments were conducted. These include large-scale simulations to perform asymptotic performance analysis and real-world validation, carried out using the reference implementation. This chapter details the evaluation protocol and presents the obtained results.

6.1 Metrics of Interest

Several metrics of interest can be defined for the evaluation of CHARON. Considering each metric's importance and the restrictions imposed by the platform used and the equipment available, the following were chosen:

- Routing
  - *Delivery ratio* is defined as the number of unique delivered messages, divided by the number of sent messages
  - *Message latency* measures the elapsed time between the creation of a message by the source and the moment when it is first delivered to the destination
  - *Hop count* or *path length* is the number of hops a delivered message travels through before reaching the sink
  - *Routing overhead* describes the number of extraneous message transmissions, i.e. those beyond the single required transmission from source to destination
- Time synchronization
  - *Clock offset* is the difference between two clocks carrying the same reference
  - *Clock drift* is the rate at which the offset increases with time
- Power management
  - *Node lifetime* is the time required for a node's battery to go from fully charged to fully discharged

6.2 Simulation

Opportunistic routing techniques are typically designed to be used in large networks with mobility — 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 [48], an open-source Java-based simulator designed for evaluation of DTN routing algorithms. Because the reference implementation was also written in Java, this option allowed for an easier conversion. It also includes implementations of several algorithms that were used for comparison.

6.2.1 Base Scenario

Settings for the simulation were extracted from the target scenario described in Chapter 3. The area of movement was defined to be 80 km^2, approximately the size of Lisbon, 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/km^2, as expected in our target scenario. A single static sink is placed in the centre of the map, shown in Figure 6-1.

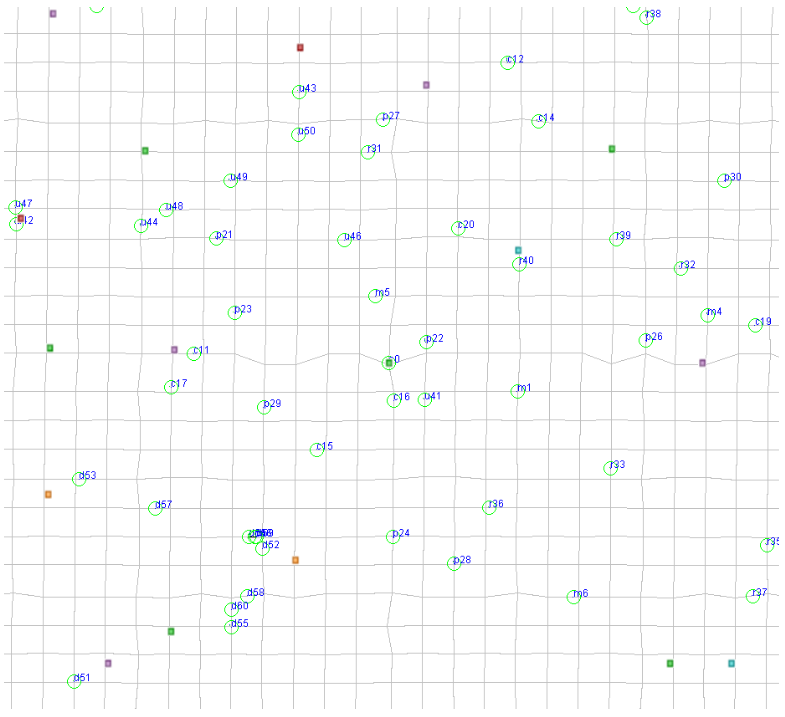


FIGURE 6-1: PARTIAL VIEW OF THE SIMULATION SCENARIO

There are six node groups, emulating a setting where different species or populations cohabit and exhibit different behaviour. Each group has a set of pre-defined 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't support more than one. Radio range (40 m) and bitrate (250 kb/s) were chosen to reflect typical values for 802.15.4 [43] 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 6-1 presents a summary of the already listed simulation parameters. These default parameters are used in all simulations, except where otherwise noted.

TABLE 6-1: DEFAULT SIMULATION PARAMETERS

Area	80 km^2
Number of nodes	60
Run duration	1 d
Radio range	40 m
Radio bit rate	250 kb/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

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, a necessity given the (real) time constraints for the evaluation.

Had more time been available, it would be preferable to execute longer simulations with longer message generation intervals and slower movement, a scenario closer to our target one.

Statistical significance is provided by the high number of messages generated during the simulation. In addition, to further reduce variance and prevent artefacts caused by irregular movement, all results are averaged from multiple runs with different seeds.

6.2.2 Results

6.2.2.1 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 6-2.

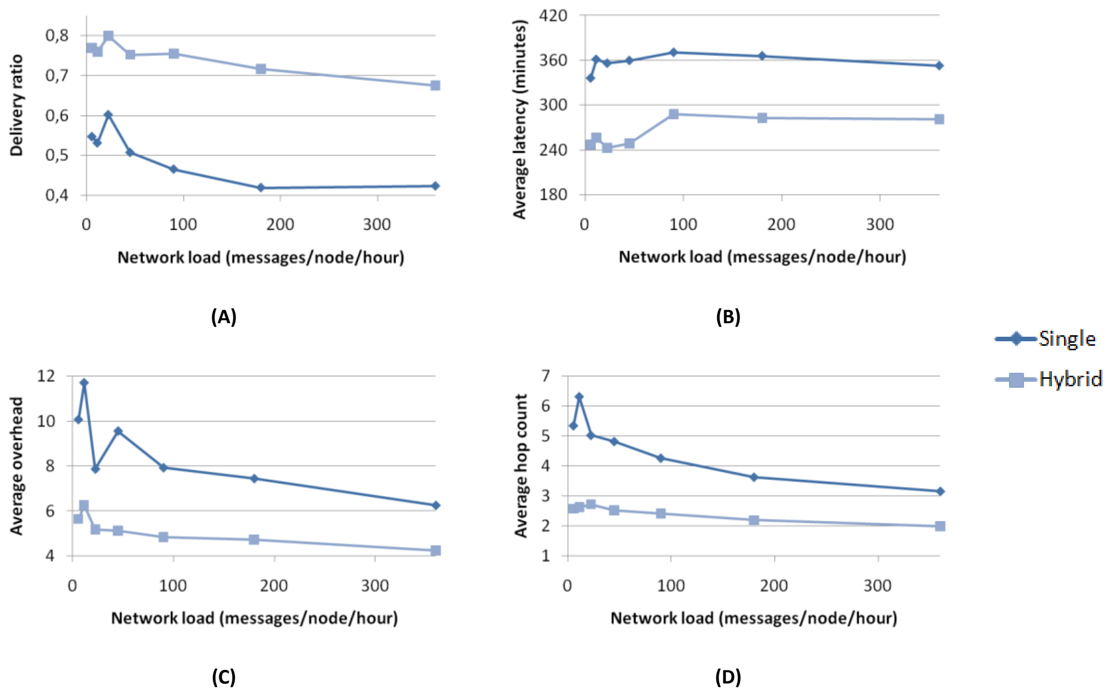


FIGURE 6-2: PERFORMANCE IMPACT OF ZOMBIES

As the network load increases, buffers start to fill up and messages are dropped or not forwarded, leading to a decreased delivery ratio. Latency, overhead and hop count also show a downward trend with increasing network load: when buffers are full, there are fewer opportunities to forward each message, and only messages generated closer to the sink tend to be delivered.

Results show a very significant improvement on all delivery statistics for the hybrid strategy, although the difference tends to be smaller with higher load, as zombies start being deleted to make room for other messages. Delivery ratio is higher due to the alternative paths created, which also reduce latency. Although overhead is lower with the hybrid strategy, in reality the number of transmissions is greater or equal: the improvement is due to the larger number of delivered messages. Hop count is, as expected, greatly reduced, showing that zombies are, in many cases, effectively being delivered prior to their parent message.

6.2.2.2 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/hour) and alarms (at a variable rate, leading to different alarm/message ratios). Figure 6-3 presents the results in several series:

- With QoS disabled, "No QoS"
- With QoS enabled
  - Alarm messages, "QoS-Alarm"
  - Sensing messages, "QoS-Sensing"
  - Overall outcome (alarm and sensing messages), "QoS-Overall"

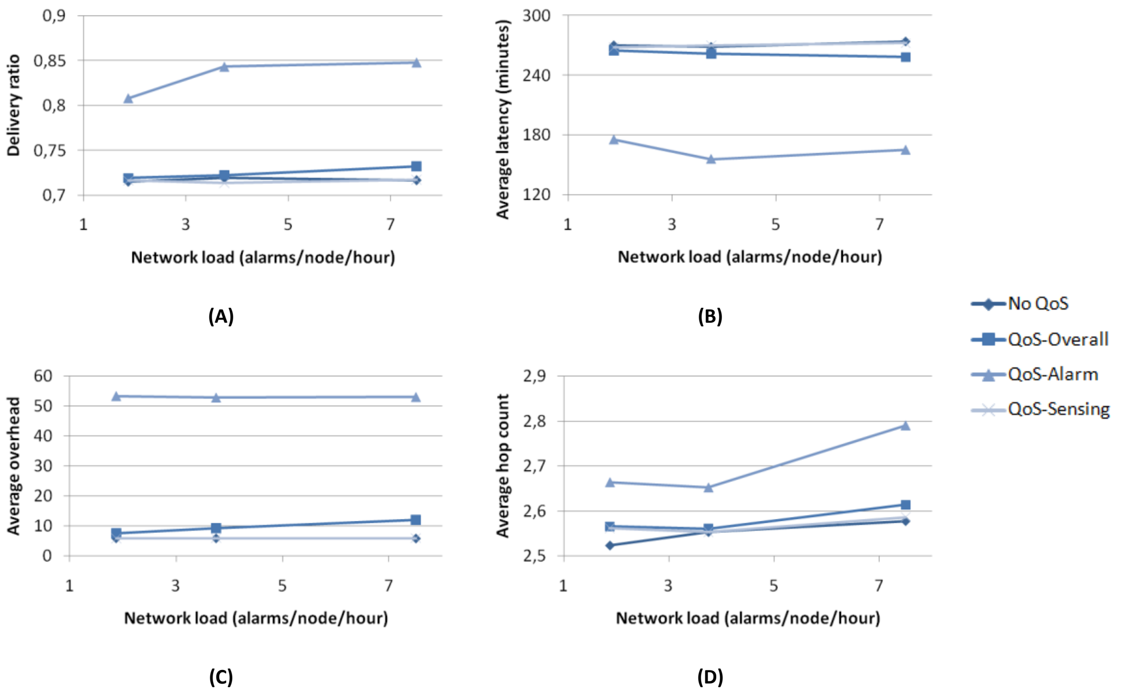


FIGURE 6-3: PERFORMANCE IMPACT OF QOS MECHANISMS

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, a clear improvement can be seen in the delivery statistics for alarms: delivery ratio is considerably better and latency is reduced by more than 40%. These improvements come at a cost of higher specific overhead, yet global overhead remains low.

6.2.2.3 Time Synchronization

Contact information was used to infer the performance of the synchronization mechanism. The simulation was started with all nodes in an unsynchronized state, and the synchronization boot-up time was measured. Figure 6-4 shows the times needed to achieve a certain percentage of synchronized nodes, with each series representing a different network size, in number of nodes.

Synchronization performance depends on the number of nodes or, to be precise, node density and unique encounter frequency. Networks with rare encounters need more time to become completely synchronized, while networks with frequent encounters synchronize quickly – nearly three times faster in the simulation.

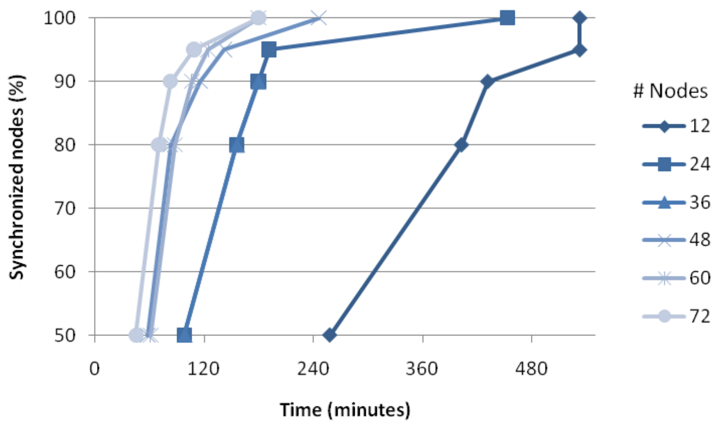


FIGURE 6-4: SYNCHRONIZATION BOOT-UP TIME FOR SEVERAL NETWORK SIZES

Even in the worst presented case, a full initial synchronization takes approximately 8 hours, and continuous reference refreshing makes it unlikely that nodes stay longer than that without receiving an updated reference. This appears to support the hypothesis that drift correction is not a critical feature of the synchronization mechanism.

6.2.2.4 Comparative Assessment

To be meaningful, the results obtained by CHARON must be compared to those attained by other routing solutions. To enable this comparison, the same set of simulations was run using CHARON, Direct Delivery [6], Spray and Wait [7], Epidemic Routing [4], and PROPHET [15]. Epidemic Routing and PROPHET are multi-copy protocols, and therefore should provide better results at lower loads. Direct Delivery is the simplest possible single-copy protocol, allowing only direct transmission from source to destination. Spray and Wait is technically a multi-copy 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 referring to multi-copy protocols. For fairness, neither CHARON nor any of the other protocols were highly tuned for this specific scenario.

6.2.2.4.1 Base Scenario

The first simulation compares algorithms' performance for a wide range of network loads. The results are presented on Figure 6-5.

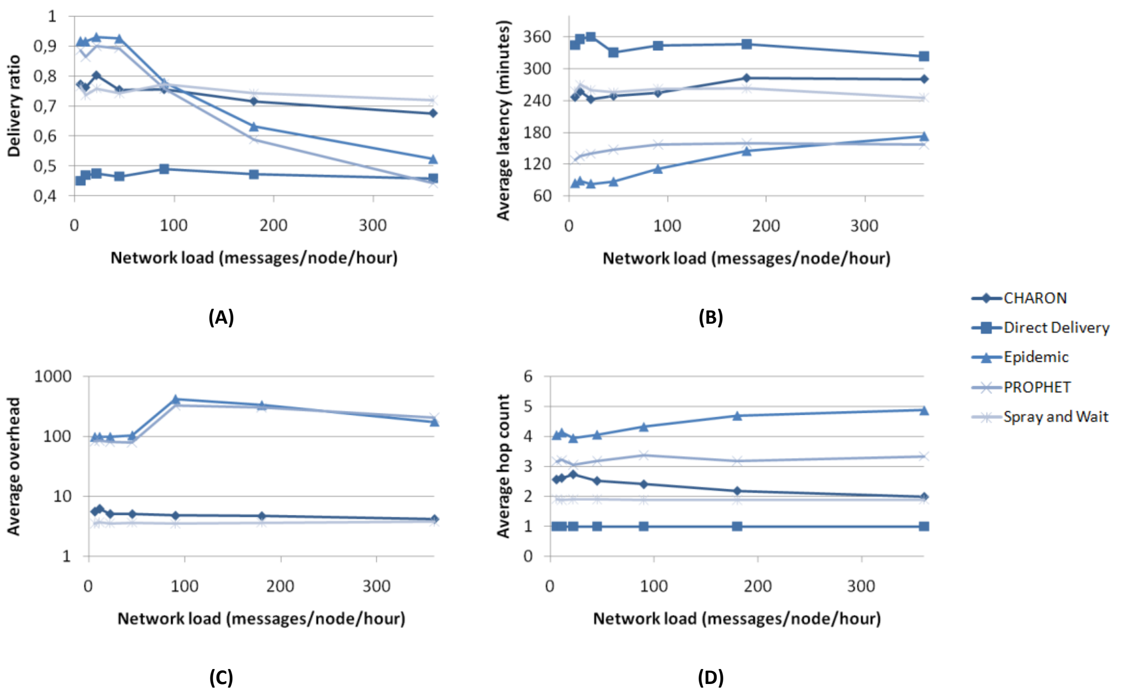


FIGURE 6-5: PERFORMANCE COMPARISON FOR VARIOUS NETWORK LOADS

Multi-copy protocols behave better under low loads, resulting in very high delivery probabilities with low latency. As load increases, specifically around 90 messages/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 multi-copy 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 – are related to the different 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 Section 6.2.2.2. Alarm classes on a QoS-enable instance of CHARON on the exact same scenario 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.

A second simulation analyses the influence of network size (in number of nodes) on the algorithms' performance. As the area of movement is constant, the node density is also being varied. The message generation period was left at the default value (60 seconds), where multi-copy approaches are still the best performers. Results are presented in Figure 6-6.

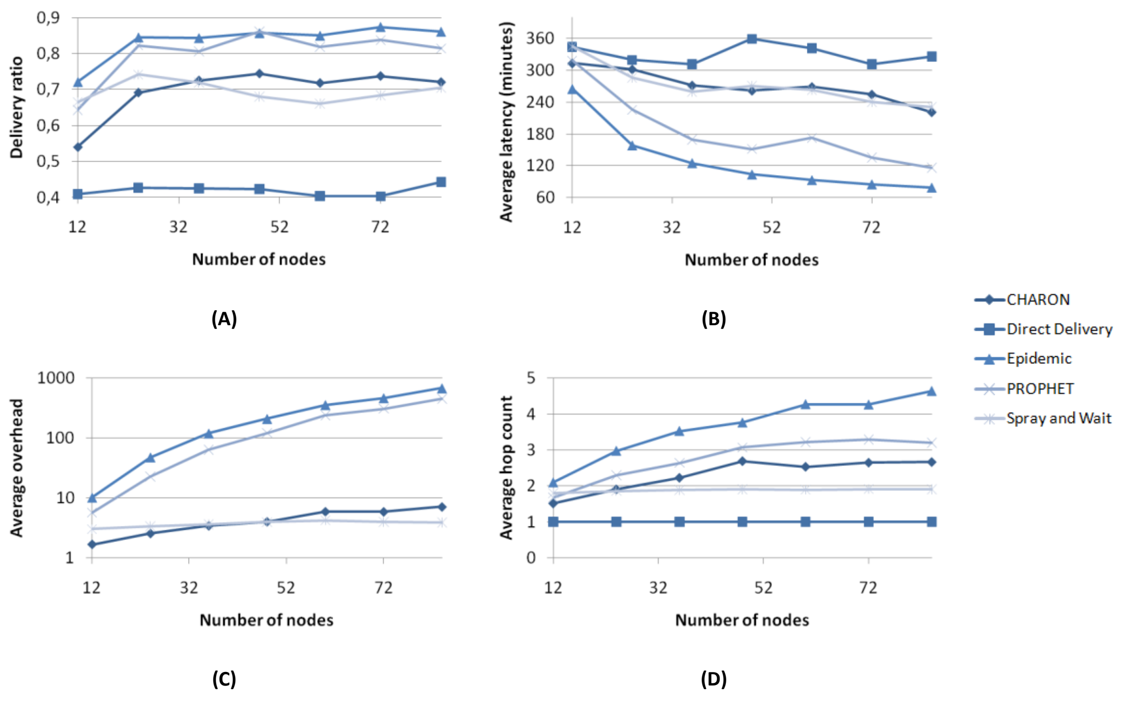


FIGURE 6-6: PERFORMANCE COMPARISON FOR VARIOUS NETWORK SIZES

Results for CHARON seem to be fairly consistent over the tested range (except in the 12 node scenario). Delivery ratio is relatively stable over the entire range but, contrary to the multi-copy approaches, neither CHARON nor Spray and Wait accomplish a significant latency reduction with the increase in the number of nodes. The lack of improvement is explained by the fact that, due to heavier constraints on the number of transmissions, these algorithms do not fully benefit from the increasing number of opportunities. On the other hand, overhead is also kept below 10 excess transmissions per message, while for multi-copy protocols it grows with network size, approaching 1000 excess transmissions for a network of 80 nodes.

Analysing the results of both simulations, some conclusions can be drawn about each protocol's performance relative to CHARON's:

- Direct Delivery always gets the worst 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.
- 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. On the other hand, it is more resilient than CHARON to changing network conditions and patternless movement, as it does not make use of historic data.
- 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.

CHARON fulfils its objective of achieving 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 too. 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 the handicap in case urgent messages need to be transferred, without a significant impact on the overall efficiency.

6.2.2.4.2 Alternative Scenarios

Simulations were also conducted using two additional scenarios, to gauge CHARON's adaptability to unplanned conditions. The first scenario is in every way identical to the base scenario, except that mobility follows a random waypoint model: nodes randomly select their destination coordinates from the entire map, and move there in a straight line. The results obtained are presented in Figure 6-7.

CHARON's performance in this scenario is markedly poor, as it is highly dependent on historic data. Epidemic Routing is the least affected, as it does not use any previous data at all.

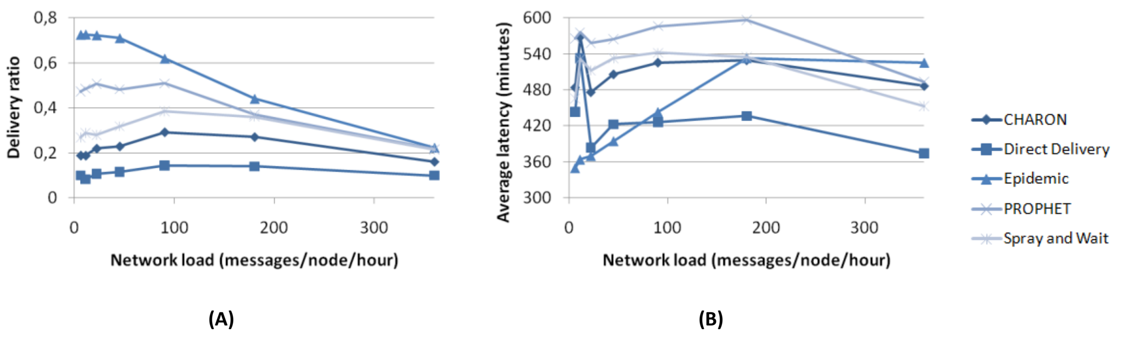


FIGURE 6-7: PERFORMANCE COMPARISON FOR VARIOUS NETWORK LOADS – RANDOM WAYPOINT

The second scenario uses a street map of the centre of Helsinki, with an area of 15 km^2, where 36 nodes (20 pedestrians, 10 cars and 6 trams) are distributed. All nodes but the trams use the same shortest path movement model as in the base scenario, selecting waypoints from a common pool. Trams move on predefined routes, as they would on real life. Node speed ranges from 2 km/h to 50 km/h. The results of this simulation are presented on Figure 6-8.

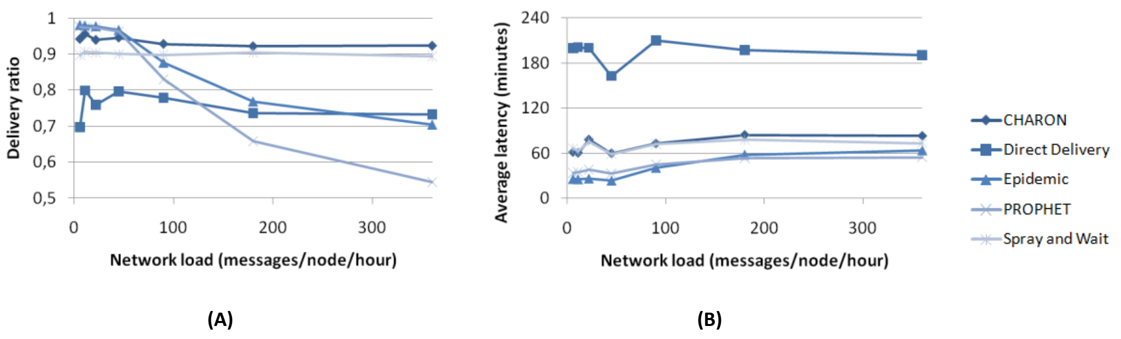


FIGURE 6-8: PERFORMANCE COMPARISON FOR VARIOUS NETWORK LOADS – HELSINKI

Contrary to the previous scenario, in this case CHARON leads in delivery ratio and achieves good results for the average latency. Interestingly, CHARON’s performance is virtually independent of the network load. The results are explained by the higher freedom of movement – which potentiates the impact of zombies – combined with faster movement that increases contact frequency and the accuracy of CHARON’s delay calculations.

6.3 Real-World Validation

The reference implementation of CHARON allowed testing under real-world conditions and using real-world hardware. That testing includes the validation of all architectural components, and a limited evaluation of the achieved performance, given the limited available resources. Tests were conducted on a laboratory (workbench) setting and on an experimental testbed.

6.3.1 Test Application

A basic test application was developed and used in most of the real-world tests. The application creates a single connection with a network-wide common stream ID. It subscribes to round events and, in each round, generates one or more messages. Each message contains one temperature and one brightness sample, for a total of 8 bytes of data. Messages are sent as monitoring data. Alarm data can be generated by pressing a button on the SPOT, but that feature was not used in the tests, as it is practically impossible to evaluate QoS influence with the available resources. Except where otherwise noted, nodes were configured with enough buffer space for 100 messages and a beacon period of 500 ms.

6.3.2 Workbench Tests

A series of workbench tests were conducted to evaluate specific mechanisms on a static setting. Four SPOT nodes and one sink (referred to interchangeably as base station) were used for these tests.

6.3.2.1 Basic Tests

The basic tests were meant to verify that the algorithm and implementation were correctly designed and working as expected. The following pass/fail tests were done:

- Routing
    - Beacon broadcast

    - EDD/ICT calculation
    - Score calculation by class
    - Correct choice of route
    - Operation in a dual-sink setting
- Forwarding
    - Message classification
    - Message transmission
    - Zombie replication
    - Behaviour under full buffer
- Time synchronization
    - Initial synchronization
    - Age verification
    - Extended periods without synchronization
- Power management
    - Round synchronization
    - Radio shutdown

The final version of the implementation passed all tests.

6.3.2.2 Routing – Static Network

Although CHARON is meant to be used in highly-mobile networks, it is foreseeable that some segments may be permanently or temporarily static. Thus, it is important that the routing algorithm works reliably in such a scenario too. To assess its performance, a test setup was prepared with four nodes in a linear setting, seen in Figure 6-9. Transmission power was tuned so that nodes could only hear their immediate neighbours. The time was set to 1.5 seconds, and the round period to 15 seconds, for a duty cycle of 10%. Nodes were configured to generate one message per round.

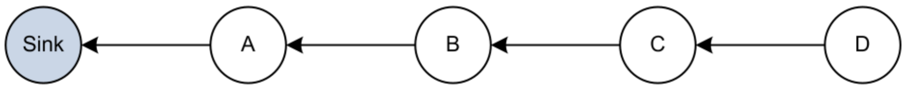


FIGURE 6-9: LINEAR TEST SCENARIO

The network was run for approximately 21 hours, until each node generated 5000 messages. The summarized results are presented in Table 6-2. No messages were lost during the experiment, and the latency average ($\overline{\Delta t}$) and standard deviation (s) are clearly correlated with the number of hops.

TABLE 6-2: DELIVERY STATISTICS BY NODE – STATIC NETWORK

		Latency (ms)	
Node	Delivery ratio	$\overline{\Delta t}$	s
A	1.0	133	87
B	1.0	1847	4051
C	1.0	5911	7740
D	1.0	15877	12318

Looking at the distribution of individual (each chart corresponds to the node with the same letter) latency values in Figure 6-10, groupings are clearly associated with multiples of the round period. Messages from node A (the closest) are all in the first group, while messages from node D (the farthest) sometimes require more than two rounds to reach the sink. Most of these cases are situations when messages cannot be routed across all hops in a single round time, a fast-forwarding situation for which the algorithm was not optimized. Some outliers are additionally influenced by late message generation, queuing and medium congestion.

The results of this test are of marginal relevance in a real setting. Not only is this type of static linear topology rare, but the delays involved are unlikely to be significant when compared to those imposed in the network's mobile segments.

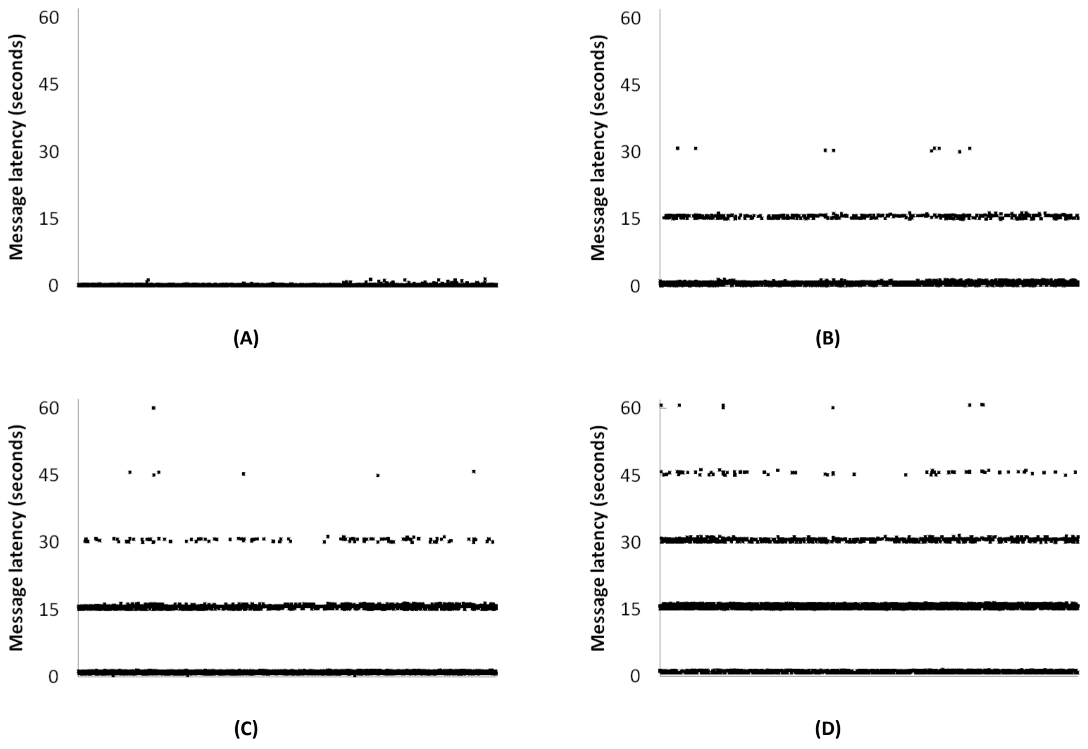


FIGURE 6-10: MESSAGE LATENCY DISTRIBUTION BY NODE – STATIC NETWORK

6.3.2.3 Time Synchronization

To evaluate time synchronization errors, 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 pair-wise clock offset. Figure 6-11 shows the testbed setup.

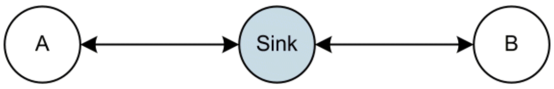


FIGURE 6-11: SYNCHRONIZATION TEST SCENARIO

Direct comparisons against the sink's reference aren't possible, as there is a non-deterministic 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.

Two experiments were carried out. In the first one, beacons were also used to update the time reference, enabling evaluation of errors in the synchronization process itself. In the second one, nodes were initially synchronized, and data was collected for a period of 3 hours without resynchronization. This experiment allowed for the determination of long-term clock drift and its influence on reference validity. In both experiments beacons were sent with a one-second period.

The first experiment ran for one hour, resulting in 3600 samples. The resulting offset average ($\bar{\varepsilon}$) and standard deviation are presented in Table 6-3.

TABLE 6-3: PAIR-WISE SYNCHRONIZATION OFFSET

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

The measured offsets are acceptable for most uses, as is the maximum absolute offset (22 ms). Figure 6-12 shows the detailed offset distribution which, as expected, approaches a normal distribution.

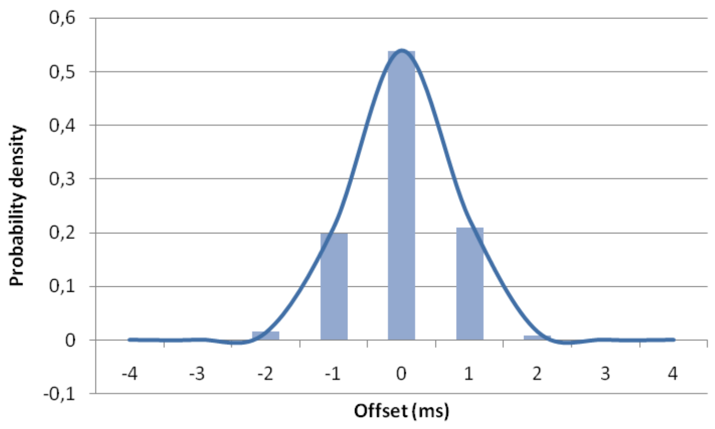


FIGURE 6-12: PAIR-WISE CLOCK OFFSET DISTRIBUTION

For the second experiment nodes were first synchronized, and samples were collected for a period of 3 h, resulting in 10800 measurements. The results obtained can be seen on Figure 6-13.

The average sampled offset linearly increases with time. Starting from an estimated offset of 0.6 ms (averaged from the first 10 samples), after 3h it averages 52.9 ms. Clock drift is estimated at 4.9 ppm by linear regression. Clock drift is specific to each clock, and further depends on environmental factors. As such, these drift values have no statistical relevance, and should be taken as an example.

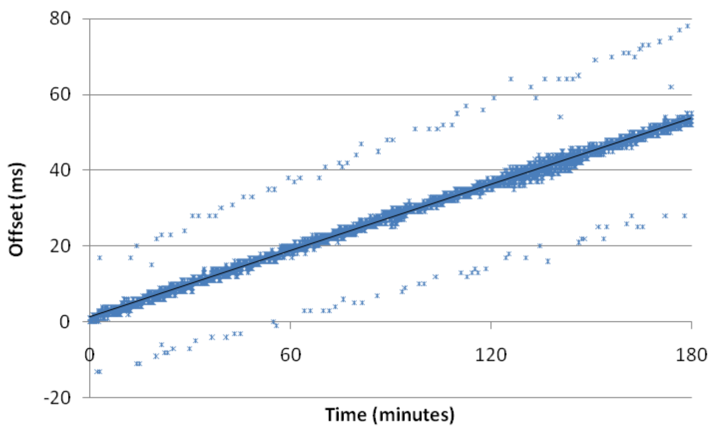


FIGURE 6-13: LONG-TERM OFFSET EVOLUTION

The results obtained show that the simple synchronization mechanism used in CHARON is able to provide reasonable precision. For the offset not to impact performance, it should stay below 20% of the round time, so nodes don’t miss too many beacons; in no condition should it exceed half the round time, as in that case a node could become completely unable to establish communication with other nodes, not even to update its reference. Using rounds of 2 seconds and the measured offset and drift values, a node would require one full day to drift more than 20%, and 2.3 days to drift 50%.

6.3.2.4 Power Management

The influence of CHARON's radio power management solution on the lifetime of nodes was measured by having a fully-charged node run the test application in contact with 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 6-4.

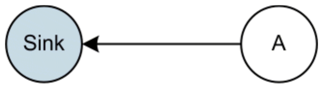


FIGURE 6-14: POWER MANAGEMENT TEST SCENARIO

In the experiment conducted on Section 6.3.2.2 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 [44], in which every node – regardless of its position – spends the majority of its round time. For this reason, and considering the long time required for each experiment, no tests were run with multiple nodes.

TABLE 6-4: 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%

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 power usage of up to 104 mA, in deep sleep it is reduced to just 33 µA, an almost negligible value [49].

Figure 6-15 plots node lifetime as a function of the radio duty cycle, showing that it follows a power law (with $r^2 = 0{,}999$) on the range analysed. Extrapolating from these results, a duty cycle of 1% would extend node lifetime to approximately 18 days, although the available data points aren't sufficient to ensure a high confidence level for this prediction.

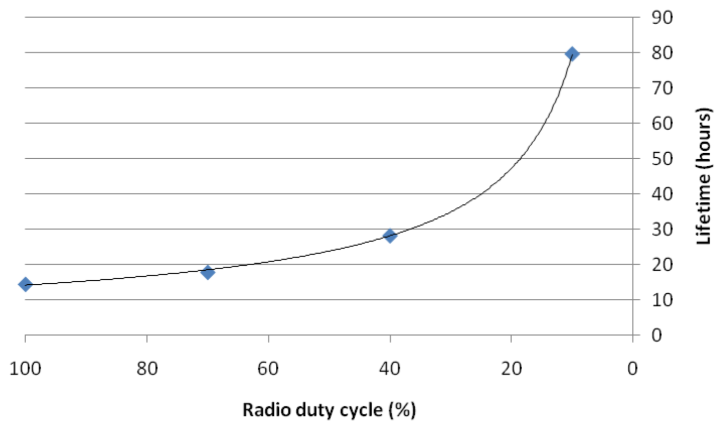


FIGURE 6-15: LIFETIME VARIATON WITH DUTY CYCLE

6.3.3 Experimental Testbed

An experimental testbed was deployed at the IST Taguspark campus, containing one Sun SPOT base station and four Sun SPOT nodes. Node mobility is provided by two LEGO Mindstorms NXT [50] robots, each carrying one of the SPOTs:

- An aerial tram, crossing the central interior garden (Figure 6-16)
- A three-wheeled rover travelling along the side corridor (Figure 6-17)

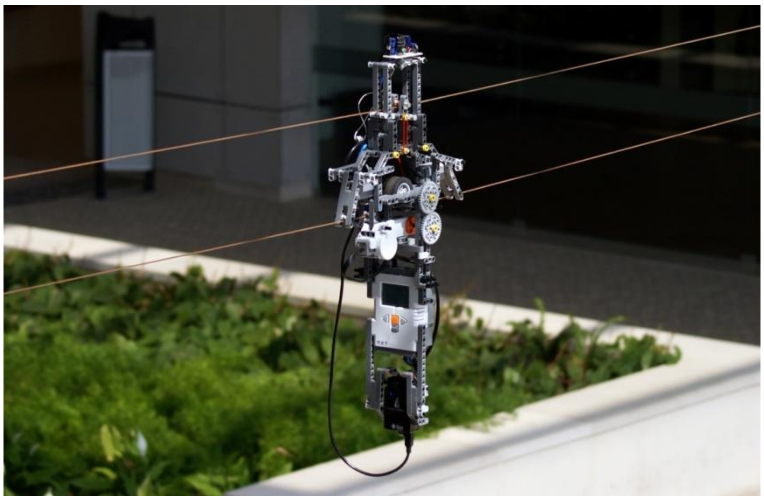


FIGURE 6-16: MESSAGE CARRYING TRAM

The tram and the SPOT it carries are powered over the rails, in order to reduce maintenance effort. The one-way trip time is 80 seconds. To reduce energy draw and mechanical wear, the robot pauses for 2 minutes after reaching the end of the line. After the pause, it resumes moving in the opposite direction, in a continuous cycle. A full movement cycle takes 6 minutes and 40 seconds. Further details on the tram's construction are presented on Annex 1.

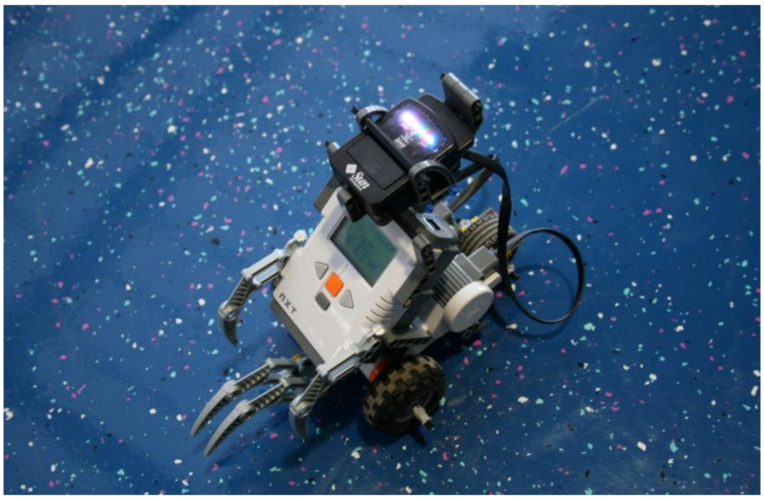


FIGURE 6-17: MESSAGE CARRYING ROVER

The rover moves in a straight line for 20 seconds, after which it rotates and pauses for 2 minutes before resuming movement. The one-way trip time is 20 seconds, and the full movement cycle takes 4 minutes and 40 seconds.

The testbed assembly can be seen in Figure 6-18. Node transmission power was adjusted to try to prevent communication other than between a static node and a carrier passing it by.

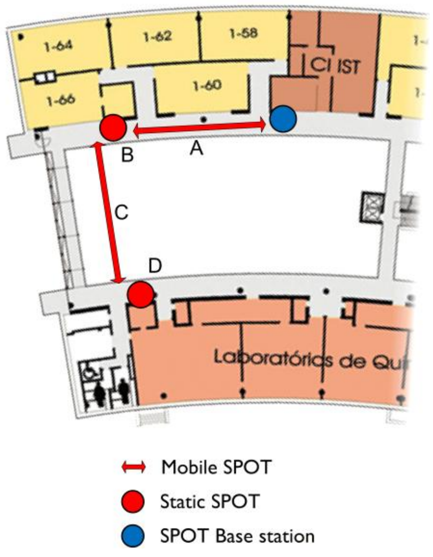


FIGURE 6-18: MAP OF THE BUILT TESTBED

A single experiment was carried out on the testbed. It was meant to evaluate the system's routing performance under mobile conditions, as opposed to the static conditions previously tested.

6.3.3.1 Routing – Mobile Network

To evaluate routing in a mobile network, the test application was deployed on the experimental testbed. The round period was set to 15 seconds and the round time to 1.5 seconds, for a duty cycle of 10%. Nodes were configured to generate one message per round. Practical considerations limited the test duration to one hour. Table 6-5 presents the results obtained.

TABLE 6-5: DELIVERY STATISTICS BY NODE – MOBILE NETWORK

		Latency (ms)	
Node	Delivery ratio	$\overline{\Delta t}$	s
A	1.0	49131	57129
B	1.0	99841	80436
C	1.0	107023	83180
D	1.0	143001	90606

The values obtained are in line with what's expected. Delays are much longer than in the static setting, a result of having to wait for the carriers to pass by. Figure 6-19 shows the detailed breakdown of message latencies, with each chart representing the node identified with the same letter.

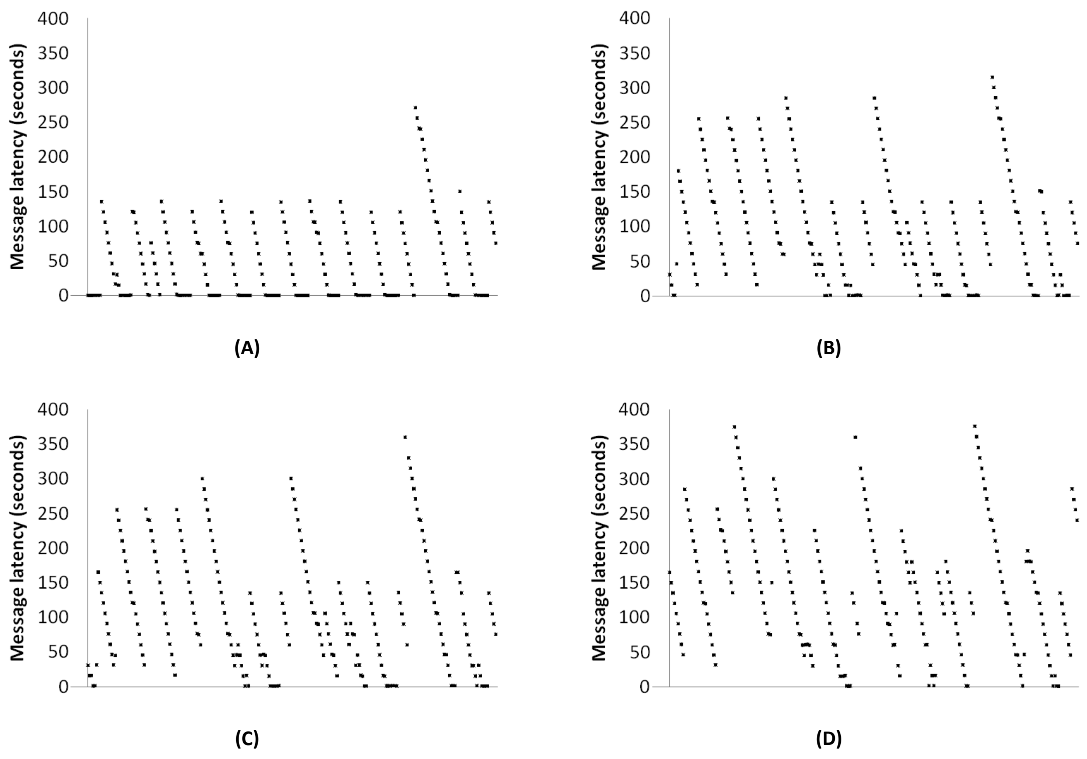


FIGURE 6-19: MESSAGE LATENCY DISTRIBUTION BY NODE – MOBILE NETWORK

Descending lines can be seen on every chart: they correspond to carrier trips. Messages are created every round time, but their latency depends on the position of the carriers involved at the time of generation. Specifically, if a message is generated by a carrier moving towards the sink, its latency is inversely dependent on the distance between the carrier and its destination. The farthest the node is from the sink, the longer these lines are.

The horizontal lines in node A’s chart correspond to the times in which the robot is parked next to the sink and messages are delivered without mobility-imposed delay. According to the defined scenario parameters, nodes should only be able to connect when in close proximity, so these lines should not be present on other nodes’ charts. The fact that they are means that, under specific conditions, communication range was long enough to create unexpected connection opportunities. The main reason for this is the positioning of the aerial tram: owing to the transmission power needed to overcome physical barriers present at close range, the tram is occasionally able to communicate from farther points in its path across an open, unobstructed area.

7 Conclusions

This dissertation proposes the Convergent Hybrid-replication Approach to Routing in Opportunistic Networks (CHARON), a new history-based opportunistic routing approach for WSNs. This approach is focused on reliability, simplicity, efficiency and flexibility. Most importantly, it aims not only for theoretical performance, but also real-world applicability.

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 significantly reduce energy waste.

A reference implementation of CHARON was developed on Sun SPOT nodes. It served as validation for the approach, and as a way of assessing its implementation complexity, which was found to be within reason for the volume of features included. An experimental testbed using these nodes was built and used to collect real-world performance information.

Extensive performance evaluation was conducted. The following are some of the most relevant results:

- In the base scenario, CHARON achieves better delivery statistics for high network loads than multi-copy algorithms, with delivery ratio never falling below 0.65. Its overhead is up to 100 times lower than that of the multi-copy algorithms, resulting in a performance-to-overhead ratio up to 80 times better. While for light loads its results are below those achieved by multi-copy algorithms, the overhead is still much lower.
- The proposed hybrid replication strategy is able to increase delivery probability by 40% to 70%, when compared to a single-copy strategy, at close to zero cost.

- The proposed QoS mechanism is able to provide multi-copy-like performance on urgent data, while routing non-urgent data with very low overhead.
- The proposed synchronization mechanism is able to provide a useful global time reference, with initial error in the single-digit milliseconds and, in the prototype platform, maintain valid references for over two days.
- The proposed power management mechanism was able to increase the prototype node's lifetime by over 440% for a conservative 10% duty cycle.
- The reference implementation was able to effectively route messages in an experimental testbed, providing important but often-overlooked real-world validation.

The results obtained show CHARON to be a valid approach to routing in opportunistic WSNs, achieving good performance with low overhead. CHARON manages to accomplish and balance the four goals initially set, providing an effective and efficient solution, that is also flexible yet still simple to understand and implement.

7.1 Future Work

There are still several challenges and paths for improvement in future work. Improvements do, however, have a tendency to increase a solution's complexity, and a cost-benefit analysis should be made prior to development. The following are some of the remaining open issues:

- More advanced uses of delay as a routing metric could be investigated and merged into the protocol. Particularly, instead of focusing only on the shortest known path, other redundant paths to sink nodes should be considered for the final calculation.
- Time synchronization is designed in the simplest possible way. This is one of the areas where limited additional complexity may be desirable. While the achieved precision is usually sufficient, it can be improved by accounting for some of the delay factors. Furthermore, the algorithm could be made more resilient against pathological cases, by considering several references instead of just the latest.
- Integrating techniques for secure routing could prove useful as WSN usage increases. At the routing level, an un-secured network allows an attacker to

perform basic denial-of-service attacks [51] by either announcing itself as a good forwarder and black-holing traffic, or injecting traffic leading to buffer exhaustion. Both problems may be solved by applying a message integrity code (MIC) to all beacon and data messages. While Sybil attacks [52] are also prevented by this mechanism, wormhole attacks [53] are still possible, as well as several non-routing-specific attacks.

- Collection of mobility information could prove helpful in many scenarios. Mobility data could be extracted from a node's previous contacts and periodically forwarded to the sink, or a list of hops could be attached to each bundle. Combined with geo-referenced static nodes, this mechanism could also provide coarse location information, valuable in an animal-tracking scenario, for instance.
- Deployment in a real WSN, followed by in-depth evaluation would, of course, be extremely helpful in identifying CHARON's usefulness in real-world scenarios. In addition to providing real-world performance data for CHARON, it would also aid in identifying weaknesses in the simulation methodology.

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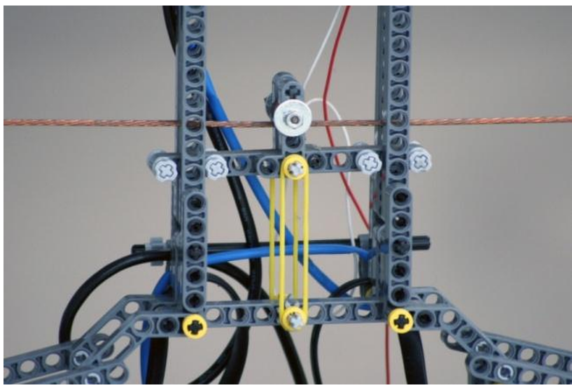
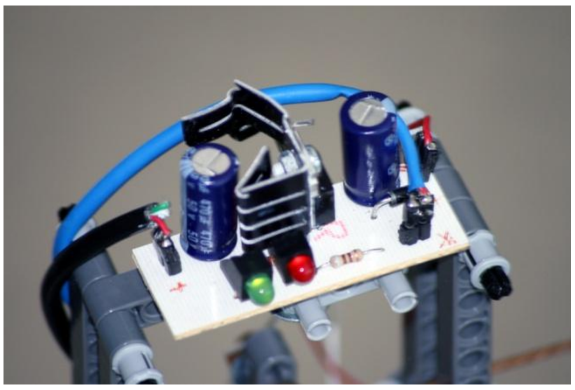
Annex 1. Aerial Tram Construction Details

There were significant challenges involved in the construction of the experimental testbed. The aerial tram, its centrepiece, includes the following main components:

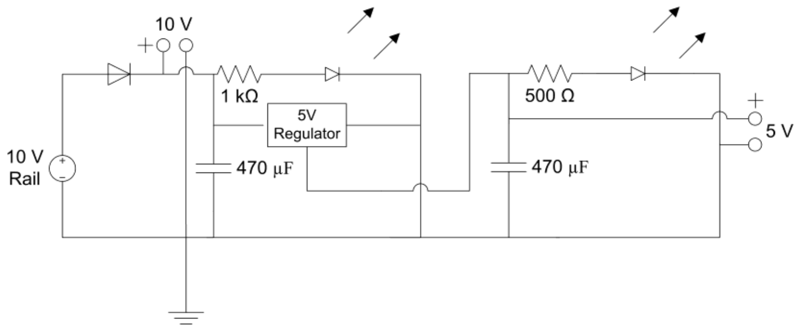
- A controlling NXT block
- A single motor for traction
- Two touch sensors
- Two custom-machined copper rollers and a power conversion circuit
- A cradled Sun SPOT node

The tram is supported by two copper cables. Mechanically, the bottom cable is used for traction, while the top one is used for stability. As the distance between both cables is not constant along their entire extension, the top support is free-moving and held in tension by two rubber bands.

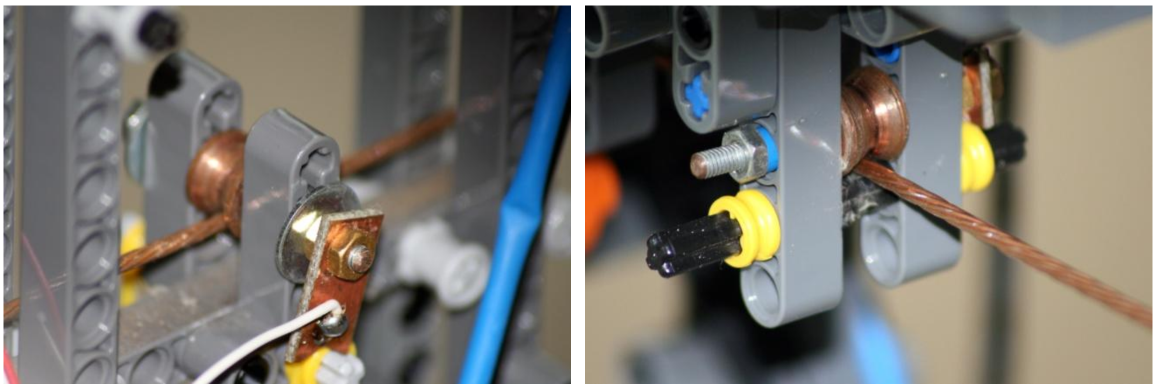




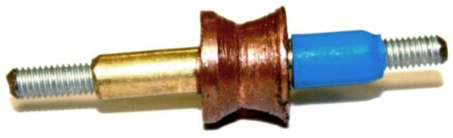
The cable pair is also used to provide electrical power to the robot, using the circuit shown below. The rails carry DC power (10 V), which passes through a protection diode to a smoothing capacitor to filter out quick disconnections due to tram movement. Power is output to both a 10 V barrel plug, connected to the NXT input, and a 5 V mini-USB plug, connected to the SPOT. The board also includes two LEDs, allowing operators to easily monitor the power status.



Power is transmitted from the cables to the circuit through two metal rollers, one placed on the top cable support and the other on one of the robot's lower cable guides. The latter also helps to reduce robot oscillation, and is accompanied by a pair of plastic rollers on the opposite side.



The used rollers were custom-machined and drilled from a 10 mm copper bar, and are 8 mm long, the same size as a typical LEGO plastic roller. They are mounted on a two-part axle, made of a drilled 4.5 mm metal cylinder bolted to an inner M3 threaded bar. The rollers rotate freely around the outer cylinder. Heat-shrink tubing was used to increase the external diameter of the axle and reduce its slippage. Two nuts are used to hold in place a blank PCB to which a wire is soldered.



The algorithm regulating the tram movement is straightforward, simply moving until a touch sensor makes contact, at which time the tram pauses for a predefined time before resuming movement in the opposite direction.

```
// d is the movement direction and t is the pause time
algorithm move_tram is
    while true then
        while (!touch) then
            move (d)
        end
        pause (t)
        d  = -d;
    end
end
```