Distributed Network Structuring with Scopes

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Abstract. Traditionally, wireless sensor networks were based on the assumption that all sensor nodes are participating in a single global application. However, it is desirable to use sensor networks for multiple concurrent applications. A key factor is the ability to dynamically structure the network into groups of nodes according to certain criteria, to later interact with the group as a whole. In this paper we present Scopes, a modular framework to support concurrent sensor network applications. A scope is a programming abstraction to declaratively define groups, which once established allow data exchange among scope members.
The main challenges in attaining these goals are network dynamics such as variable node density, topology changes and node churn. We demonstrate the feasibility of the concept by achieving rapid scope propagation, high scope reliability and efficient data exchange.

1 Introduction

Traditionally, the instrumentation of an environment with a wireless sensing and control infrastructure has been realized with one particular application in mind. Scenarios such as home, building and industrial automation, however, all face the need to exploit the installed resources for multiple, concurrent applications [1,2]. Consider for instance a smart building, where applications such as HVAC control, motion sensing for light switching, and fire detection could all run simultaneously, simplifying the infrastructure. Established architectures such as ZigBee's, and the support for multiple modules [3] and multithreading [4] indeed allow node-level concurrency. We argue that these solutions fall short in offering a clear network-level mechanism to exploit resources when multiple applications run concurrently, leaving the developer with the responsibility of selecting the subset of network nodes on which applications run.

Another shortcoming of current systems is their management. The large and dynamic amount of devices that comprise the wireless network make prevalent node classifications such as coordinator/router/end-device in many cases

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insufficient for the development of distributed sensor network applications. Several solutions facilitate manageability through the intuitive idea of node *groups* [5,6,7,8,2]. A group's extent has a direct implication on its energy cost. One-hop neighborhoods are the cheapest by exploiting the broadcast mechanism [5]. Multi-hop groups covering larger network regions have also prooved useful [6,8]. We think that creating logical groups spanning nodes which are potentially scattered throughout the whole network is important for many applications.

In this work we present Scopes, a framework that tackles the aforementioned issues. We show its feasibility through real-world experiments on a sensor network testbed. A scope is simply a group of nodes defined by a set of criteria. Scoping criteria are defined declaratively and are logical predicates on static or dynamic attributes. Of importance for this approach is the *rapidness* with which a scope definition is propagated and becomes functional, the *reliability* in covering all nodes meeting a scopes criteria, and the *stability* against network dynamics. We obtain very good results for all three aspects. Scopes are automatically maintained by the framework, coping with network changes. Once created, a scope enables a bidirectional communication between the scope's creator and its members. We analyze the goodput and link-level message exchange for both directions and different traffic patterns. Our measurements show good channel utilization, particularly up to an order of magnitude improvement over the baseline routing protocol for traffic originating from member nodes.

Section 2 presents a brief overview of the major concepts of Scopes and the framework design. Section 3 contains the detailed evaluation of Scopes according to the above mentioned aspects. We conclude the paper by presenting related approaches (Section 4) and our major findings (Section 5).

2 The Scopes Framework

Scopes is a modular framework that enables multitasking by bringing a logical structure to the network. With the Scopes framework, nodes are organized into groups, which we call scopes (to distinguish we will use the lower and upper case form throughout the document). A scope is the central abstraction provided by the framework to applications. A scope can be defined by means of a logical expression, which must be satisfied by a node to become its member. Once a scope is created, it continues to exist until it is explicitly removed, even as nodes fail or if they temporarily leave and rejoin. The framework takes care of reliably maintaining the scope membership.

We have designed a declarative language to create and delete scopes[1]. We exemplify the most important constructs within the building automation scenario above, shown in Table 1. Imagine we want to define a scope `HVAC_Outlier` over HVAC equipment nodes not within room temperature limits, so that the heating output can be adjusted. An application running on this scope reports

[1] For space reasons, we do not fully describe the Scopes language syntax in this paper. The reader is referred to the project site, www.dvs.tu-darmstadt.de/research/scopes, for a detailed description.

the id and position of the member nodes. `HVAC_Outlier` is satisfiable by nodes with a temperature sensor, whose temperature is outside the range (20...25), and the user-defined variable `ATTACHED_TO` equals `hvac`. Properties included in an expression may have a more static (e.g., `ATTACHED_TO`) or dynamic (e.g., `TEMPERATURE`) nature. Dynamic properties are very powerful, but their use is expensive since every change results in a re-evaluation of the scope membership expression. Finally, scopes can be nested and therefore form a hierarchy. Nested scopes specialize a scope definition by implicitly restricting the membership condition of their parent-scope. For example, if a scope `Room22` is defined over all nodes in room 22, the scope `Room22MotionNodes` could specialize it by selecting those nodes additionally possessing a motion sensor. The latter can then be used to detect motion and switch lights correspondingly. Every scope has a parent-scope; top-level scopes have an artificial parent-scope called *world*, which includes all available nodes. A node that does not belong to any scope is member of the *world*. Conceptually speaking, nesting scopes contributes clearer definitions and better organization. Technically, they reduce the communication overhead thus improving the performance and the energy efficiency.

```
CREATE SCOPE HVAC_Outlier AS (
  ATTACHED_TO = 'hvac' AND
  EXISTS SENSOR TEMPERATURE AND
   (TEMPERATURE <= 20 OR
    TEMPERATURE >= 25) );
```

```
CREATE SCOPE Room22MotionNodes (
    EXISTS SENSOR Motion
) AS SUBSCOPE OF Room22;
```

Table 1: Scope declarative definitions

External (i.e. out-of-network) applications can resort to this language to create scopes. Such expressions are parsed and flattened into a pre-order network format specifically designed for sensor networks. This format is descriptive enough to accommodate the necessary expressions, yet compact enough to typically fit in one network message. Scope creation requests are then handed over to a node, e.g., over a serial port. In-network applications can also construct scopes by resorting to this predefined format. Any arbitrary node can be used to create a scope (termed the *scope root* node), however in practice we observe two cases. Scopes created from gateway (sink) nodes have global and permanent character. Regular nodes in most cases create localized neighborhood scopes for tasks such as event detection.

Scopes enable a bidirectional communication channel between the member nodes and their root node. The framework can operate with multiple routing algorithms. Any routing algorithm supporting bidirectional traffic and multiple concurrent routes can be used. Each top-level scope can be dynamically configured to use any routing algorithm; subscopes inherit it implicitly. Separating the definition of a scope from the underlying routing algorithm potentially enables scopes to span across different node platforms, and allows other optimizations through the choice of diverse routing algorithms.

The concepts in Scopes were originally conceived to provide loose coupling in traditional networks [9]. These were later proposed for sensor networks in an earlier paper [10]. In this work we materialize them, and show their feasibility for the cited sensor network scenarios.

2.1 Design and Implementation

We have built Scopes for both Contiki [11] and SOS [3]. These are the first operating systems to enable runtime code distribution and loading. The Scopes framework is composed by two main modules, `ScopeMgr` and `ScopeMembership`, which perform all the management and provide API's to the upper (concurrently running) applications' layer and lower routing layer. For each scope, the `ScopeMgr` module maintains information like timestamps, scope properties, or id of the root node. The `ScopeMembership` module evaluates the local membership condition given a scope definition and the node's properties (Section 2). When a property changes, a scope reevaluation is triggered locally. This yields minimal energy consumption overhead as no communication is needed, only CPU cost.

The `ScopeMgr` module interacts with the *routing layer* to send and receive data, and to signal scope membership updates, which can be used to optimize the memory management of routing tables. We have implemented two routing algorithms, namely *flooding* (FLD) and an extended version of *gradient-based* (GBR) routing [12]. Scope creation requests are similar to the *interests* in Directed Diffusion [13], thus GBR is also inspired by it. Directed Diffusion only supports communication towards the sink, therefore we extended the tree construction to establish routes in both directions. To avoid traffic congestion, we also implemented a rejection mechanism: if a node is rejected by a busy node, it will try connecting to another neighbor, achieving extra reliability at the cost of some message overhead (we evaluate this aspect in the next section). Both algorithms were implemented as separate modules, hence they can be deployed dynamically.

The Scopes API. The ease of use of Scopes is best illustrated by its API:

```
send_scope_create(parent_scope_id, scope_id, propLen, properties)
send_scope_data(scope_id, sendDirection, srcApp_id, destApp_id,
                msgType, payloadLen, payload)
send_scope_remove(parent_scope_id, scope_id)
```

To create a scope, applications call the `send_scope_create(...)` method. The `ScopeMgr` module sends a scope creation message to all potential scope members: if it's a new top-level scope, it is sent to all nodes; otherwise it is only sent to members of the parent scope. Whenever a node becomes a member of a scope, this is signaled to applications that have registered to receive this information. Once a scope has been created, a bidirectional data channel between the scope root and its members is established, which can be used by invoking `send_scope_data(...)`. After finishing its task, an application can delete its scope by calling `send_scope_remove(...)`. A removal message is then sent to the member nodes. In addition, applications can register for notifications about the dynamic scope membership changes. These are asynchronously delivered to them, avoiding polling.

Automated Maintenance. To address communication unreliability, topology changes and the update of dynamic properties, we developed a *scope refresh* mechanism. Inspired by a simple video keyframe technique, we employ two types of beacons, or *scope refresh messages*: *simple* and *full*. The former implement a keep-alive mechanism, which indicates that a scope is still active. They are small-sized, thus save communication and computation energy. The latter trigger a full scope reevaluation, and contain the full scope definition. This increases message size, but allows a reevaluation of the scope definition at all nodes (belonging to the parent scope), as well as at newly added nodes. Scope refreshes can be arranged as sequences of relatively inexpensive simple refreshes followed by a full refresh[2].

Once a scope is removed, no further refreshes are sent. In case some nodes miss the removal message, a configurable local lease will timeout. The scope is invalidated and marked for deletion, associated resources are released. If the root node of a scope fails, scopes created at other nodes are not affected. Also, if the network gets physically partitioned, the partition that includes the scope root remains unaffected. Due to the missing connectivity to the root, nodes in the other partitions assume a failure of the root node and automatically invalidate the scope to save resources. After network reconnection and upon a full refresh, the nodes reevaluate their membership and resume their tasks.

3 System Evaluation

To evaluate the Scopes framework we have conducted numerous experiments on our live testbed. The CS-building building testbed comprises 30 TelosB nodes, powered through USB hubs (see Figure 1), distributed over 9 offices and spanning $544m^2$. At each room, nodes are located either next to the windows or above fluorescent lamp tubes. The building's thick walls greatly reduce radio ranges, forcing a multi-hop behavior even at the maximum transmission power level (0 dBm).

Scopes. In our tests we have used the scopes depicted in Figure 1. These represent reasonable, real-life scopes. The scope S_1 covers all nodes. Such scopes are necessary, e.g., for massive software updates. Scope S_2 emphasizes that membership is not necessarily given by physical proximity, instead scopes build overlays.

[2] In this work we investigate the worst case behavior of using only full refreshes, and postpone the analysis of this optimization as a topic for future work.

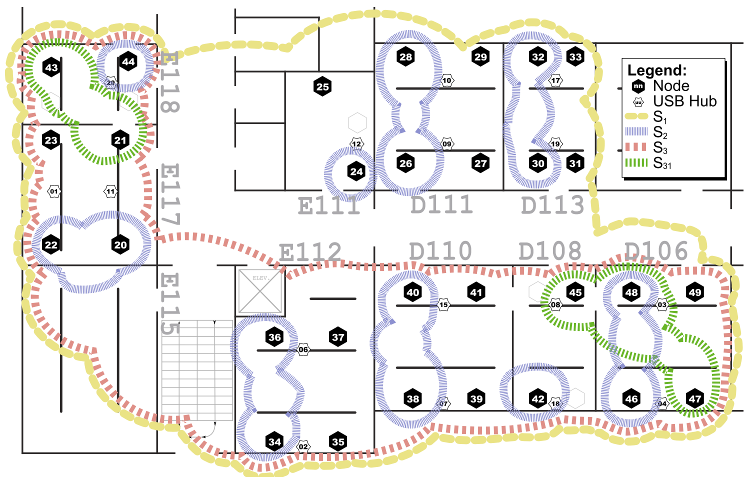


Fig. 1: *Piloty* building testbed and scopes used

Finally, S_3 and S_{31} illustrate nested scopes. These occur in any hierarchical relation, for instance, in domain organization. The scope definitions were based on operations on node IDs, although as explained before, other relations over node properties such as location could have been used. Table 2 summarizes the used scopes. The last column presents the size of scope definitions and the entire creation message. These highlight the compactness of the representation. Lastly, all scopes were created at the network boundary, namely node 43 (top left). This forced a minimum of 2 hops and an avgerage of over 3.

Scope	Description	Parent Scope	Size	
			Scope Def.	OS Message
S_1	All nodes	*world*	4 bytes	18 bytes
S_2	Nodes with even id	*world*	74 bytes	88 bytes
S_3	Nodes whose $id < 24 \mid\mid id > 33$	*world*	9 bytes	24 bytes
S_{31}	Node id $\in \{21, 43, 45, 47, 48\}$	S_3	24 bytes	38 bytes

Table 2: Summary of employed scopes

There are two important aspects to the framework, namely *reliability* and *efficiency*. In the next subsection we discuss how reliable the scope mechanism is and its relation to the underlying routing protocol.

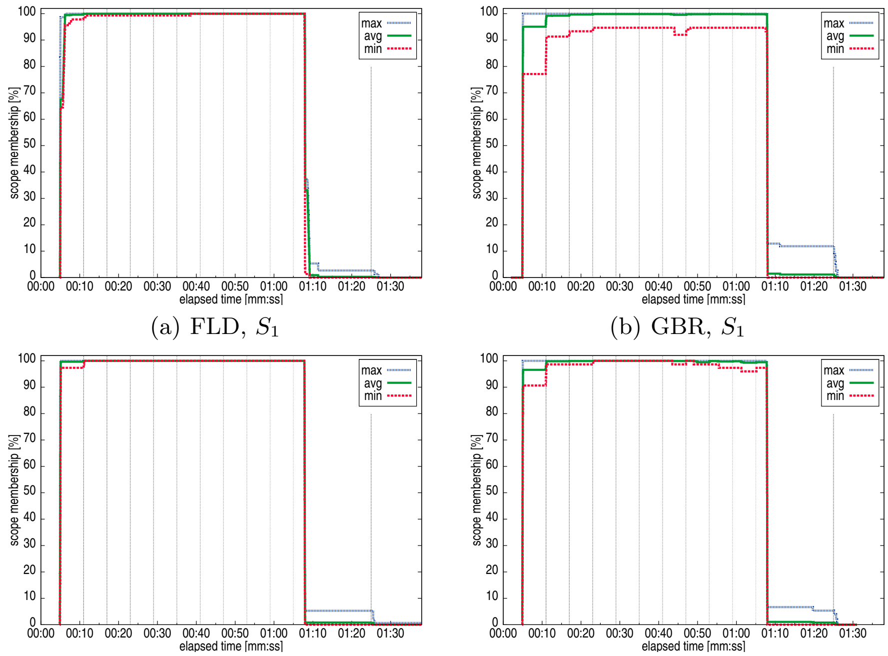
3.1 Scope Creation, Removal and Maintenance

We first investigate the two main scope operations, *creation* and *removal*, together with the scope *maintenance*. Consider the scope membership described by a function, $\phi(t)$, that outputs the percentage of nodes which belong to a scope out of an expected set at a given time t; ϕ: $\mathbb{Z} \rightarrow [0,1]$. The ideal membership $\phi_I(t)$ is a function of time which equals 100% when the scope is alive and 0% otherwise, that is, resembles an instantaneous scope creation and removal. The values observed in practice, $\phi_R(t)$, lag behind the ideal values, i.e., once a scope is created it takes time for nodes to reach a high membership percentage, and later when a scope is removed it takes time to drop down back to 0%. This is natural and due, e.g., to message propagation delays and medium loss. When multiple test repetitions are considered, we refer to $\phi_{R_{max}}$, $\phi_{R_{avg}}$ and $\phi_{R_{min}}$ as the maximum, average and minimum membership values, respectively.

Scope reliability is described by three parameters. First, the reliability *level* stands for the deviation of the average measured membership percentage values from the ideal ones. To quantify the reliability level, the area between the curves ϕ_I and $\phi_{R_{avg}}$ is calculated. The lower the value is, the closer $\phi_{R_{avg}}$ is to ϕ_I, thus the higher the reliability level. Second, the *stability* of the scope mechanism indicates its tolerance to network dynamics. This is quantified by calculating the area between the curves $\phi_{R_{max}}$ and $\phi_{R_{min}}$. Again, the lower the value, the more stable the membership is. Last but not least, the *rapidness* in achieving an expected membership percentage is important. We quantify the *creation* and *removal delay* by measuring the time it takes for $\phi_{R_{avg}}$ to arrive to $\sim$100% after a scope creation, and to 0% after a scope removal, respectively. Clearly, the lower these values, the better.

In Figure 2 we characterize the reliability of the framework for S_1 and S_2 (the behavior of nested scopes is evaluated in detail later) The figures present $\phi_{R_{max}}$, $\phi_{R_{avg}}$ and $\phi_{R_{min}}$ as defined above. A scope is always created at t=0:05 and remains alive for 63 seconds, thus, $\phi_I(t)$ is 100% between t=0:05 and t=1:08, and 0% elsewhere. This scope lifetime allows for 10 refreshes at a period of 6 seconds (indicated with vertical dashed lines drawn at regular intervals). The rightmost dashed vertical line indicates the last point at which all nodes should automatically remove themselves from the scope in case the explicit scope removal message wasn't heard. This occurs 20 seconds after the last refresh (t=1:25).

The plots for S_1, 2(a) and 2(b) show that the creation delay was quite low: it occurred immediately with FLD, while it took 3 refresh periods with GBR. For both algorithms, the scope membership was kept up at around 100% until the explicit removal was requested. Later, once a scope was removed, almost all nodes heard the explicit removal message. Virtually no nodes resorted to the lease expiration timer with FLD (0.26%), while for GBR it was below 5% – an acceptable value. The removal delay of GBR was thus higher than FLD's (only after the lease expires did nodes automatically release resources). While the reliability levels were similar (FLD got 0.62% while GBR's was 0.63%), FLD's stability (2.09%) was better than GBR's (6.32%). As mentioned before the values for reliability and stability are the deviation to the ideal or min/max curves. The plots for S_2 exhibit a slightly lower reliability level. The scope creation delay worsens for FLD, requiring 1 refresh period, and GBR showed an unstable scope



(a) FLD, S_1

(b) GBR, S_1

(c) FLD, S_2

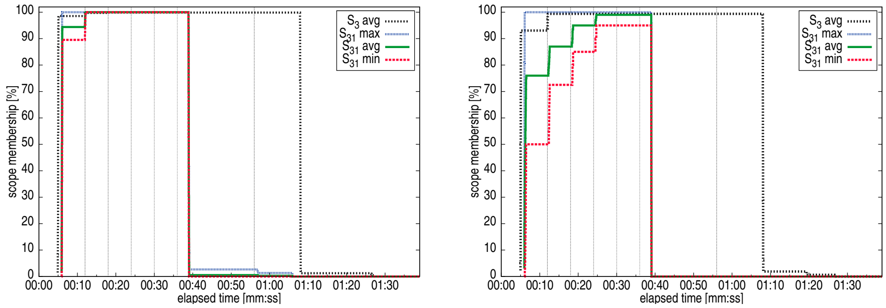
(d) GBR, S_2

Fig. 2: Scope creation, removal and maintenance for FLD and GBR

membership percentage. The results show that both approaches are viable in practice.

Nested Scopes. We now evaluate the behavior of hierarchical relations among scopes. In these tests, we created scope S_3 at t_1, and one second later created subscope S_{31}. While S_3 remained alive (as before) during 63 seconds, S_{31} remained alive for 33 seconds, which allowed for 5 refreshes to be issued.

Figure 3 presents the respective reliability results for FLD and GBR. Again, while both protocols reached high scope membership percentages, GBR (99%) was slightly lower than FLD (100%). The reliability levels were high in both cases: FLD achieved 0.51%, while GBR got 2.95% (lower is better). Also, FLD was more stable than GBR (1.78% vs. 8.89%). The scope creation delay was of 1 refresh period for FLD and 3 for GBR, whereas the removal delay was 20 seconds for FLD and 0 seconds for GBR. These results point out that nested scopes exhibit similar reliability properties to that of top-level scopes.



(a) FLD (b) GBR

Fig. 3: Scope creation, removal and maintenance for nested scopes S_3 and S_{31}

Network Density. We now discuss the effects of network density on scope operations and maintenance. Particularly, we consider the effects of density with respect to the reliability of the scope operations.

There are two main effects that influence the reliability. On one side, the more nodes there are, the higher the redundancy available to build the underlying scope overlays, thus the reliability level increases. On the other side, the more nodes there are, the more collisions there can occur, which decreases the reliability level and stability.

We inspected this issue by repeating all of our tests with three node density values. These configurations are presented in Table 3, with the resulting density in nodes per m^2. The amount of nodes per room is indicated with ρ.

ρ	#Nodes	Density
4	30	$1/18.1m^2$
2	18	$1/30.2m^2$
1	10	$1/54.4m^2$

Table 3: Node densities

Figure 4 summarizes the reliability level results for different densities. In general terms, we can say that the denser the network, the higher the reliability level (lower values). Also, and despite the outlier <FLD, S_2, ρ=2>, here it is observed that S_1 is more reliable than S_2.

Scope Operation Costs. The energy costs associated to the scope operations are largely due to messages sent and received. Evidently, energy efficiency depends on the routing mechanism chosen. We studied the operation cost in isolation, in a typical usage these become marginal compared to data exchange. Figure 5 plots link-level traffic for S_1 and S_2. Each measurement point represents one test run (2 minutes), there were 25 runs. The curves confirm the expected routing algorithm behavior. The behavior exhibited by FLD is deterministic, since the decision whether a node is member of a scope or not is totally local: a test run requires around 340 scope management messages regardless of the scope definition. In turn, GBR pays the price of the increased reliability of the acknowledged reverse paths. This overhead, in contrast to flooding, does depend on the number of member nodes. Therefore, S_1 exhibits a constant factor of 2x, while for S_2 it is 1.5x.

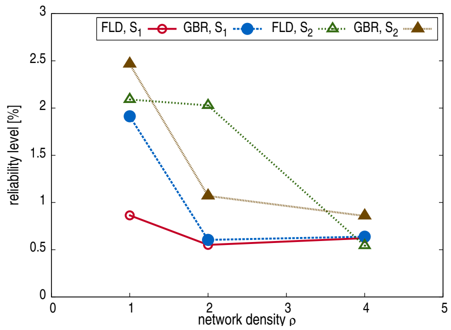


Fig. 4: Density tests for S_1 and S_2

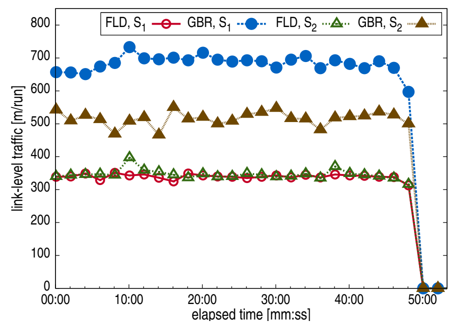


Fig. 5: Scope operation costs

3.2 Scope Traffic

We proceed by evaluating the bidirectional data channel described in Section 2.1. As important metrics, we consider *goodput* and *link level message exchange*. While the former refers to the end-to-end application layer traffic, the latter indicates the in-network traffic needed to obtain that goodput. We have designed our traffic tests as illustrated in Figure 6. During the first $[t_0, t_1)$ and last $(t_4, t_5]$ stages, there's no activity. A scope is created at t_1, and remains alive until it is removed at t_4. In order to allow the scope to stabilize after its creation and removal, we introduce an initial delay of α and a wait of β seconds (respectively). Traffic itself occurs during (t_2, t_3).

The two traffic directions, root-to-members (RtM) and members-to-root (MtR), were tested separately. For the RtM tests we chose α=15s and β=3s. This large α value allows the scope to stabilize through two refreshes before data transmission starts. For the MtR tests we chose α=3s and β=20s. Here, a short α was sufficient, but a larger β was needed to account for removed (i.e., unstable) nodes. More importantly, since sensor network applications are diverse, we concentrate on two communication patterns: periodic and bursty traffic.

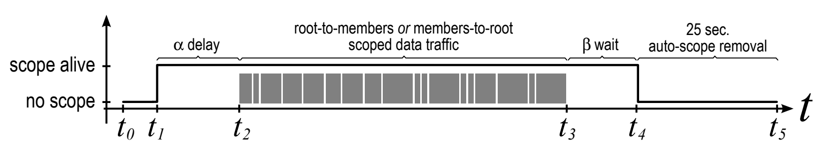
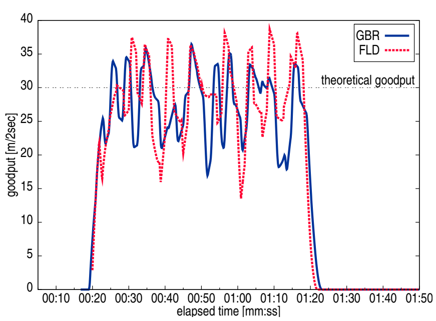


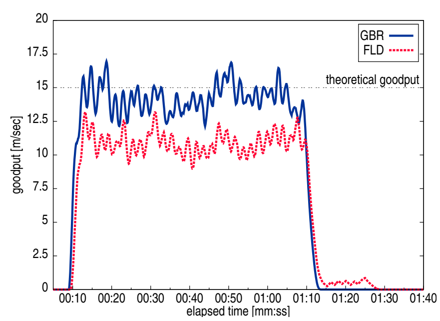
Fig. 6: Test sequence for scope data traffic

Periodic Traffic. These tests encompass, e.g., monitoring applications. Here, in RtM tests, the scope root sends $M = 30$ messages to the members, whereas in MtR tests each scope member sends M messages to the root. Each sending node posts a timer that is triggered with a frequency $\lambda = \frac{t_3 - t_2}{M} = 2$ seconds. To reduce network collisions, message transmission is delayed randomly by ε (with $\frac{\lambda}{8} \leq \varepsilon \leq \frac{7\lambda}{8}$) by the sending application. To further stress the routing protocols, we used scope S_1, which includes all 30 network nodes.

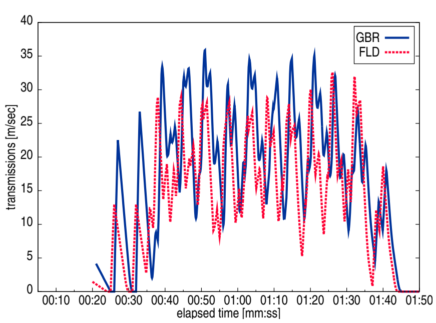
The top two plots of Figure 7 present goodput results both for RtM and MtR. (Note that RtM was sampled every 2 seconds, thus the theoretical goodput is 30 [messages/2 seconds], while MtR was sampled every second, thus the theoretical goodput is 15 [m/s].) The RtM goodput plot, 7(a), shows that both protocols have similar goodput. FLD showed an average goodput of 96.44%, slightly above GBR's 91%. The MtR goodput plot, 7(b), does however show a clear advantage for GBR (95.44%) over FLD (74.44%). This was to be expected since flooding causes too many collisions, while GBR restricts the data flow to those links whose gradient values are high. The tail exhibited by FLD was due to a node that got automatically removed from the scope at the middle of the test and then heard a refresh, hence re-started sending messages.



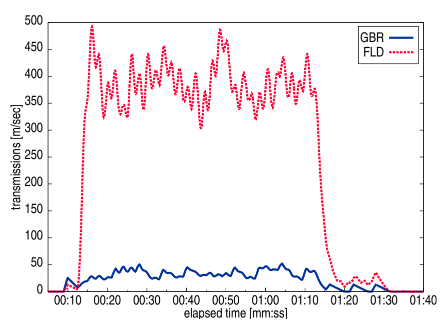
(a) root-to-members goodput



(b) members-to-root goodput



(c) root-to-members link-level traffic



(d) members-to-root link-level traffic

Fig. 7: Goodput and link-level periodic traffic

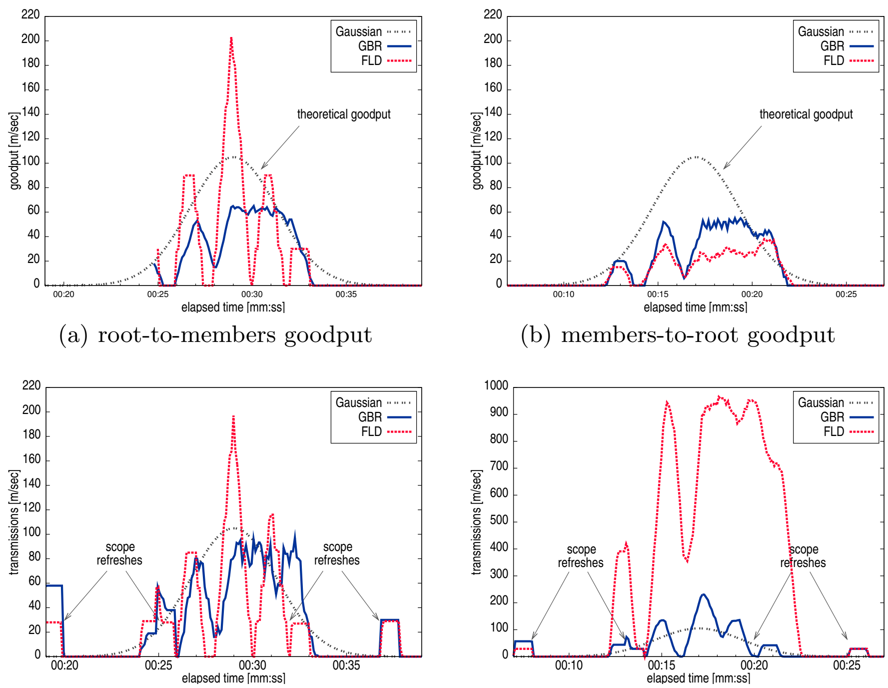
In the bottom plots of Figure 7, the link-level traffic is shown. These curves include both data and scope management traffic. The MtR plot, Fig. 7(c), exemplifies that the typical usage yields marginal management overhead. GBR transmits 15% more messages than FLD due to the acknowledgment and reject messages. This increase in link-level traffic constitutes an upper bound for GBR's overhead compared to FLD. The biggest difference between the routing protocols becomes evident in Fig. 7(d). GBR is one order of magnitude better than FLD: it induces less than 9% the messages required by FLD. This constitutes GBR's main strength and outbalances any scope maintenance overhead, even under the chosen adverse test conditions.

Bursty Traffic. The following tests encompass event-based applications such as object-tracking, where bursty traffic is the predominant pattern. A message burst is produced in two cases: when an event-subscription is to be disseminated rapidly from the subscribers to the publishers (RtM traffic), and whenever a set of nodes detect an event and need to notify the subscriber (MtR traffic). To support bursts, however, several mechanisms such as route lookups and concurrent medium access via the MAC protocol must tolerate stress.

For the bursty tests, sending nodes produced a message burst which can be approximated by a gaussian function with center=5, standard deviation=2.3 and a peak value of 7. This amounted to a total of M=15 messages. As with the periodic traffic, the burst is ideally sent in intervals of λ=2 seconds, and scope S_1 was used for the experiments. In the RtM tests, it is only the scope root node who sends the burst, while in MtR tests, all 30 (member) nodes sent the burst back the root.

The results presented in Fig. 8 include both data and scope management traffic. The theoretical values are represented by the Gaussian curve. Figures 8(a) and 8(b) display the goodput for RtM and MtR traffic, respectively. In the RtM tests, GBR produced a goodput of 78.62%, while FLD's was 99.77%. In the MtR tests, FLD got 44.54% and GBR got 69.19%. Further, the graphs show that in terms of burstiness, FLD was superior to GBR. While FLD exhibited the expected behavior, GBR showed a high latency. This was due to GBR reaching a maximum bandwidth. While FLD uses the capacity of all communication links to send messages, GBR restricts the nodes' out-degree. This sets a capacity along the established routes. Hence, under the same load, GBR needs more time to transport the message burst.

Figures 8(c) and 8(d) show the total RtM and MtR traffic, respectively. All of the qualitative statements regarding the burtiness and latency made above hold here as well. As for throughput, we can claim that both FLD and GBR reach the maximum. While FLD utilizes the complete network capacity, GBR's traffic is lower. The significantly better GBR efficiency over FLD for MtR – an order of magnitude – is clearly visible in 8(d).



(a) root-to-members goodput

(b) members-to-root goodput

(c) root-to-members link-level traffic

(d) members-to-root link-level traffic

Fig. 8: Goodput and link-level bursty traffic

4 Related Work

The concept of Scopes offers a powerful tool to *select* nodes in a sensor network. This feature is also pursued by other approaches. In Generic Role Assignment [7], a set of roles is distributed throughout the nodes, which must decide to which of these roles they belong. A node choosing a role may trigger other nodes to reevaluate their role membership, leading to instability and thus messaging overhead. This can't occur in Scopes, as a node's membership decision can't affect that of other nodes. Hood [5] and Abstract Regions [6] provide a *neighborhood* programming abstraction through which *physical* neighbors may interact with each other. By leveraging the omnidirectional broadcast medium, Hood supports efficiently a node's one-hop neighborhood, while Abstract Regions extends it to multi-hop neighborhoods defined by properties like hop count or radius. Another system, Melete [2], focuses on disseminating code over groups, which share some of the concepts with Scopes. Membership is defined with small boolean bytecode functions, which we believe to be too low level. Our scheme for selecting nodes is most similar to that of *logical neighborhoods* and its Spidey language [8]. Here, nodes export *attributes* which are comparable to node properties in Scopes. While with Spidey the user has to decide how much effort the system should employ (through the concepts of *credits* and *hop count*) in searching for matching nodes, this is transparent in Scopes since a scope is network-wide. Also, logical neighborhoods have a transient character, since they have to be specified in each message, while scopes have a more permanent character and are stored locally. Finally, logical neighborhoods resort to a tight integration with the routing algorithm, which we intentionally avoided in order to offer alternatives depending on the desired traffic type.

5 Conclusions and Future Work

In the present paper we described Scopes, a programming abstraction featuring declarative definition, automatic maintenance, and efficient data exchange. We also introduce an improved routing algorithm based on Directed Diffusion, and use flooding as a baseline for our comparisons. We experimentally investigated various aspects of the concept and the infrastructure such as scope operations, maintenance and traffic.

We conclude with the following remarks: high *reliability* levels with low-power routing algorithms were achieved under the experimental conditions (∼0.60%). Scopes achieve high and stable scope membership percentages (∼ 100%) for both routing algorithms, though gradient-based routing exhibits low-power characteristics. Scopes exhibit rapid reaction (adaptation). This means that the framework efficiently uses the available resources - not more than needed, not longer than needed. Similarly, nested scopes exhibit analogous reliability properties to that of top-level scopes. High bidirectional throughput is achieved. In the most practicable use case, i.e., the traffic from scope members to the root, gradient-based routing is an order of magnitude better than flooding, both for periodic and bursty communication patterns. Both algorithms are equal for traffic from the root to the scope members. All of the Scopes evaluation experiments are performed in a *real-world environment on a live testbed.*

With the scope abstraction, the visibility of the sensor data in the network can be controlled, since messages are only exchanged through network paths between scope members. The increased privacy is only apparent to applications, since it cannot serve as privacy-preserving technique. We are currently integrating Scopes with security aspects to ensure privacy control.

In our design, we opted for using a single routing algorithm for both traffic directions instead of two specialized algorithms for each direction. This will be improved, as we want to work on an automated routing algorithm runtime selection and tuning for a specific scope.

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