A Mediated Gossiping Mechanism for Large-scale Sensor Networks

Frieder Ganz, Payam Barnaghi, Francois Carrez, Klaus Moessner
Centre for Communication Systems Research
University of Surrey
Guildford, Surrey GU2 7XH
Email: {f.ganz, p.barnaghi, f.carrez, k.moessner}@surrey.ac.uk

***Abstract*—Gateways in sensor networks are used to relay, aggregate and communicate information from capillary networks to more capable (e.g. IP-based) networks. However Gateway-to-Gateway (G2G) communication to exchange and update information among the gateways in large-scale sensor networks for query processing, data fusion and other similar tasks has been less discussed in recent works. The requirements for large-scale sensor networks such as dynamic topology and update strategies to reduce the overall network load makes G2G communications an important aspect in the network design. In this paper, we introduce a mediated gossip-based G2G communication mechanism. The proposed solution leverages the publish/subscribe approach and uses high-level context assigned to publish/subscribe channels to enable the information discovery and G2G communications. Gateways store/aggregate sensor observation and measurement data according to specific context which is defined based on features such as spatial and temporal attributes, observed phenomena (i.e. feature of interest) and sensor device features. The gateways communicate with each other to exchange data and also to forward related queries for data aggregation in cases that the data should be aggregated from two different sources. The proposed solution also facilitates reliable sensor service provisioning by enabling gateways to communicate and/or forward requests to other gateways when a resource fails or a sensor node becomes unavailable. We compare our results to probabilistic gossiping algorithms and run benchmarks on different dynamic network topologies based on indicators such as number of sent messages and dissemination delay.**

I. Introduction

Sensors will play an important role in our future daily life. Research areas such as the Internet of Things, Smart Homes, Smart Environments, Ubiquitous and Pervasive Computing utilise Wireless Sensor Networks (WSN) to observe human users and physical world phenomena. In the past years, sensing devices have become cheaper and easier to program. The increasing trend of using sensors in different environments and applications has led to an exponential growth in sensor networks [1]. Gateways running on computer systems and high-capable devices such as mobile phones can be used to access and manage the sensor networks. A sensor network gateway acts as a bridge between the low-level networks and higher-level applications and end-user. The gateway components, in a large-scale sensor network with many gateways, form an overlay network that handles the data that emerges from the underlying network [2].

In sensor networks, communication between the gateways and propagating the data and available services, as the size of network and consequently the number of gateways grow, becomes a challenging task. The requirements for large-scale sensor networks such as dynamic topology and update strategies to reduce the overall network load are also important issues that are supported by enabling communication between the gateways in distributed sensor networks. Gateway-to-Gateway (G2G) communication to exchange and update information among different gateways for query processing, data fusion, scalability and reliability is an important aspect that enhances the performance of data communication in sensor networks and can also enable to save power on resource constraint devices. In conventional static network topologies, queries can be routed from one node to the next one with the assumption that the nodes are available at any time. However, in changing sensor network environments nodes can join and leave the network due to factors such as battery outage, natural obstacles and mobility. These changing environments demand communication protocols which either adapt to dynamic topologies or are robust against changes. Gossip or Epidemic Protocols are often used in distributed environments where the topology is decentralised and dynamic. In this paper, we present a deterministic node selection strategy for the gossiping protocol based on the context of the sensor nodes. The context of a sensor node in this work refers to current status of the node and also the environment variables. The context attributes include features such as location, capabilities and the feature of interest that is observed. The solution is based on our previous work described in [3] where we use a context model. The model is adapted from the W3C Semantic Sensor Network Ontology[1] to describe the attributes and current features of sensor nodes. The sensor nodes use a negotiation mechanism to identify available gateway nodes and after handshaking with them, nodes are associated to the closest gateway in the network. While associating to a gateway, the sensor nodes publish their context information into the gateway repository (for more information refer to [3]). In the current work, we utilise the context information from the published sensor nodes that define what they observe and/or measure related to what feature of interest. We form groups based on the published context information and the gateway

[1] http://www.w3.org/2005/Incubator/ssn/XGR-ssn-20110628/

TABLE I
PERFORMANCE OF PROBABILISTIC GOSSIPING

Nodes	Rounds	Messages
10	4	10
100	8	200
1000	11	3000
10000	15	40000
25000	16	109949
50000	17	234949

nodes logically assigned to the groups based on type of context that they are able to provide.

Queries to discover and access the sensor data in the proposed framework are distributed in two-steps. First they are routed to the gateways which are responsible for the queried topics and then in the second step and after identifying gateways holding related context data, they are forwarded to the capillary network within the set of nodes that are associated with those gateways. This means each gateway will publish what type of context it is capable of measuring and capturing and the query processor will first identify the related gateways and then the query will be forwarded to related capillary networks to access the data. The G2G communication and data/query propagation is performed through a mediated gossiping mechanism that attempts to maximise the probability of discovering queried sensor data in a distributed network.

In the reminder of this paper, we first introduce gossiping based mechanisms in Section I-A and then describe publish/subscribe methods. Section I-C describes sensor network and middleware component requirements for these networks. In Section II gossiping methods used in middleware for sensor networks discussed. Section III introduces our deterministic gossiping approach which is evaluated in Section IV and Section V concludes the paper and discusses the future work.

A. Gossiping Algorithm

In Gossip Protocols [4], N nodes communicate in a peer-to-peer communication to exchange data with other nodes. The decision is made random or deterministic on which node will communicate next. The underlying networking aspects are not part of the gossiping algorithm and it is assumed that node to node communication via multi-hop is supported by lower layers. The messaging mechanism is divided into virtual rounds where in each round i a node can send a message to another node. Therefore in each round the number of nodes which also start gossiping increases exponentially. This leads to fast and reliable information dissemination. In a network of N nodes the maximum number of rounds will be $O(log(N)) + O(ln(N)) + O(1)$ rounds where in each round the distribution of nodes that do not send any messages follows the exponential distribution $p_{i+1} = p_i e^{-(1-p_i)}$ with $O(Nlog(N))$ as the number of messages sent. Table I shows that the random gossiping approach leads to fast dissemination but high traffic in the network which is especially in power-constrained environments is not desired.

B. Publish/Subscribe Mechanism

The Publish/Subscribe pattern is an event-driven mechanism where publisher announce topics or channels on a specific subject. All subscriber to a topic will then receive messages if an event is occurred. In WSN this kind of information propagation methods is mainly used in monitoring scenarios when sensors observe an object and send alert messages in case of a change in the observational measurement. This leads to less energy consumption compared to pull (query) approaches as data is only transmitted if changes are observed by the sensing node. In this work, we assume that the sensor nodes will propagate the observation and/or measurement data to the gateway if a change in the physical world is occurred. The gateway nodes can store the received data in a repository for temporary use (i.e cache). The queries are then forwarded to the gateway that hold the data on the contexts that are related to a query. If a requested data is not available in the gateway repository the query would be forwarded to the underlying network. The gossiping method is applied in two scenarios, when a change is observed in a node and when data is requested, the information is sent via a gossip-based mechanism to the gateway. This type of propagation also enables data aggregation as the data is transmitted via multiple hops. In the same way, a query can be also propagated in the capillary network while attempting to maximise the likelihood of accessing the requested data by traversing less numbers of hops.

C. Middleware for Sensor Networks

In this work two different kind of nodes are considered:
a) resource-constrained sensor devices communicating via IEEE 802.15.4 standard with simple measurement capabilities (temperature, light, accelerometer) and cheap production cost such as TelosB, SunSpot and ZigBee devices.
b) high-capable devices such as mobile phones which support several ways of communication such as IEEE 802.15.4 to communicate to the constrained devices but also GPS, 3G, LTE , Wi-Fi and bluetooth, and higher production cost. This devices or other high-capable computer systems are used to run the middleware that connects sensor nodes with higher-applications and end user interfaces . The devices are able to form a Peer-to-Peer (P2P) overlay network to support larger spatial areas.
The sensor nodes can connect to the gateways through a zero-configuration and discovery approach as introduced in [3].In brief, the solution specifies that nodes register themselves to the nearest station and submit their meta-data which include available capabilities and other related node information. The middleware saves this data, annotates it with further context information and integrates it in the overall context model. Based on the available capabilities and the context information the middleware can publish topics to which other applications can subscribe to. The topics are also represented in a semantic representation which are published automatically each time that new information is available (e.g join/leave of sensor node).

II. Gossiping mechanisms in Sensor Middleware

There are a number of middleware solutions for WSN that are described in different work such as [5], [6], [7], [8]. The existing solutions mainly bridge the gap between low-level network layers and higher application layers and provide access to the underlying sensor networks by introducing service and/or application interfaces.

Mires [9] is a publish/subscribe based middleware for sensor networks that utilises topic concepts similar to our context model to access sensor data. However it does not provide a scalable and extensible mechanism to publish the topics for various application domains. In our approach, we focus on large distributed sensor networks and maintain scalability in accessing data from these networks. We utilise gossiping mechanisms which are commonly used in computer-to-computer communication. The gossiping mechanisms are known to scale well in large networks independently from the topology of the underlying structure with easy implementation.

The main flaw in gossiping algorithms is the number of messages to inform the entire network. In [2] an approach is introduces to split the network into several sub-graphs based on network-related metrics. The sub-graphs then form intra and inter cluser links where the fan-out of those clusters is analysed in terms of reliability according to the underlying topology.

Spatial Gossiping based algorithms [10] communicate with nodes in a spatial area d to inform nearby nodes first and/or to group nodes in the same area. Our approach is not limited to a spatial parameter d as we extend this model to any distance defined in a context model. This includes spatial information, hierarchical information (subclass relationship), and other patterns defined through relationships in the semantic model.

Voulgaris *et al.* [11] describe a peer-to-peer overlay network which exploits the structure of the underlying information and proposes methods to semantically group them. In our approach, we use the existing semantic model and form groups based on the relationship between similar concepts.

III. Context-Based Mediated Gossiping

To reduce the number of communicated messages in the gossip protocol while retaining the fast dissemination, we propose a deterministic node selection. A network is virtually split into semantic similar groups based on the context information of the network. This leads to a new N^* which is defined as N/C where C is the number of the introduced groups. This limits the messaging only to a certain group. The groups are defined by generating sub-graphs that are referred to as overlay networks. The overlay networks are constructed according to the structure of high-level concepts (i.e context definitions) in a model and form a logical network. The context information is stored in a semantic model based on the W3C Semantic Sensor Network Ontology where concepts are linked based on different relationships. Using the model, virtual groups are formed based on their subClass relationship in the context model. This approach is not limited to spatial information and can also be applied to other relationships defined in the context model.

As shown in Figure 1, groups are created based on the

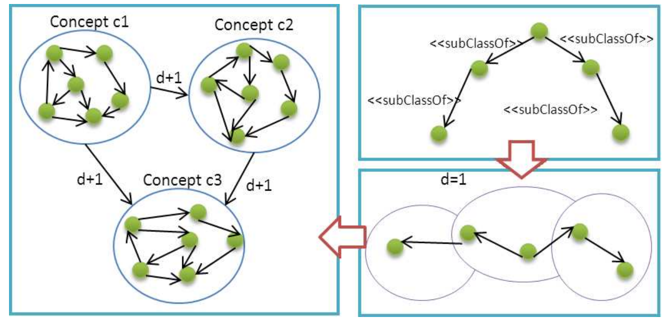

Fig. 1. Context based grouping

relationships defined in the context model. This leads to two different types of connections, intra-group connections where nodes of one group communicate with each other and inter-group connections where nodes of different groups communicate. The degree of linking and therefore the reliability of the overlay network and the gossiping algorithm depends on the fan-out of the inter and intra connected nodes. The fan-out in turn depends on the underlying topology. This concept is further discussed in the Evaluation section. The following describes the grouping and context publishing processes.

1. Contact: New sensor nodes join a gateway node and submit their capabilities according to the protocol defined in [3]

2. Annotation: The gateway annotate the capabilities with the available context information such as location and/or observed object and links them to a concept *c*.

3. Topic Publication: The Gateway gossips the new topics in a semantic distance d to its close neighbours. To keep a connection between the different groups the high-level concept of the group is gossiped to the remaining network within a semantic distance of $d + 1$.

4. Topic Location: Topics can be found and subscribed to by reasoning over the context model to find gateway nodes responsible for a certain concept.

5. Event Publication: When a new event occurs, the responsible gateway gossips the information to the nodes in the same group and to the a node in the semantic distance $d + 1$. The main advantage of using a publish/subscribe pattern in this scenario is that messages related to a certain event are only published in one group which limits the overall traffic of the network.

The semantic distance d describes the number of sub concepts in one group. In a semantic distance of one, all nodes are split into one group which can be inferred through one step in the context model. The next group is formed by clustering all nodes which are one step further (one class level above) away from the initial concept *c*. The communication is therefore divided into two steps, the intra-communication between nodes in one group and the inter-communication between the groups. This method is useful for G2G communication and when the gateway hold different data that can be related to a requested query according to different attributes. The same groups in capillary networks can be used to mediate the gossiping mechanism. In this paper, our focus is on dissemination and propagation of data and queries between gateways and between the nodes in the capillary networks. Different clustering methods can be used in the capillary network to form the logical networks within the network. The clustering solutions are not in the scope of this paper and a survey on clustering solutions for sensor networks can be found in [12]. We assume that the nodes are formed in the logical groups within the capillary network and then introduce the mentioned gossiping mechanism. For G2G communication, the relations between topics and the structure of the context is used to form the logical groups. For example, gateways that provide environmental monitoring data can be assigned to one specific group. The environmental monitoring can be then divided to different sub-categories such as surface monitoring, water control and underwater sensors. To evaluate the current approach we annotate a set of predefined concepts. In a real world scenario a topic-context model for this purpose is also required. The topic-content model can be created using common ontologies and frameworks that are used to specify concepts and their relationships in different domains.

IV. EVALUATION

In this section we compare our deterministic approach with the random based gossip mechanism and a simple flooding mechanism. The comparisons are provided in terms of sent messages, dissemination rate and reliability according to the underlying topology. We assume that the group count is given by $C = log(N)$. To compare the rate of dissemination we have to consider that in the deterministic approach we first have the intra group communication and the communication between the different groups. This requires an extra round to inform the network, see Fig. 2; However it decreases the overall number of messages (see Fig.3). To demonstrate our results we introduce a statistical simulator to run benchmarks on different topologies.

The dissemination rate is based on how many rounds are needed to inform each node in the network of a given change triggered by an event. The flooding scales well in small networks as each node propagates the information to the neighbour node and the amount of neighbournodes compared to the overall network size is high. However in large networks a node has only a small number of neighbours and messages spread only from a defined starting point.The worst case of rounds needed to reach the whole network is O($\sqrt{N}$) with a message number of O(N) This could be utilised to spread information to the nearest neighbours first, but this is not covered by this benchmark.

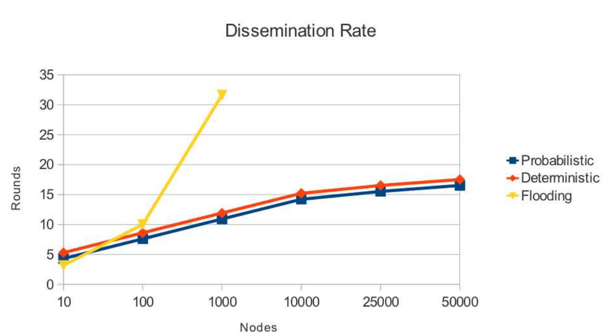

Fig. 2. Dissemination rate of different mechanism

The probabilistic approach compared to the flooding mechanism converges faster as in each round a node starts gossiping. This leads to an exponential growth in transferring messages. The probabilistic gossiping in the one hand accelerates dissemination but on the other hand it increases the message amount. In our deterministic approach, the context-based grouping gossiping is only performed inside the groups and then relayed to the next group which needs an extra round to complete the dissemination. This method decreases the message count which can lead to reducing the energy consumption.

Assuming that for each message transfer the nodes use radio communication and subsequently use restricted power sources, reducing number of message communication using the proposed solution enables reduction of the power consumption.

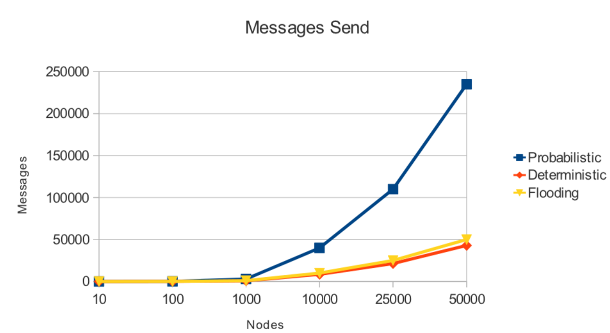

Fig. 3. Message amount of different mechanism

The performance of the algorithms depends on the fan-out and the inter linkage between the nodes and the groups [13]. The algorithms perform well up to a certain failure rate as described in [14]. To evaluate the algorithms in a practical scenario we developed a simulator software.[2] The software is able to generate different random network topologies with different interlinkage patterns such as power law distribution and small world properties.

Figure 4 shows a screenshot of a randomly generated network with 100 Nodes with an average fan-out of 5 and small world properties in which each node is connected to any other node by a maximum number of 7 hops.

[2]the software is available at http://purl.oclc.org/net/unis/dmw

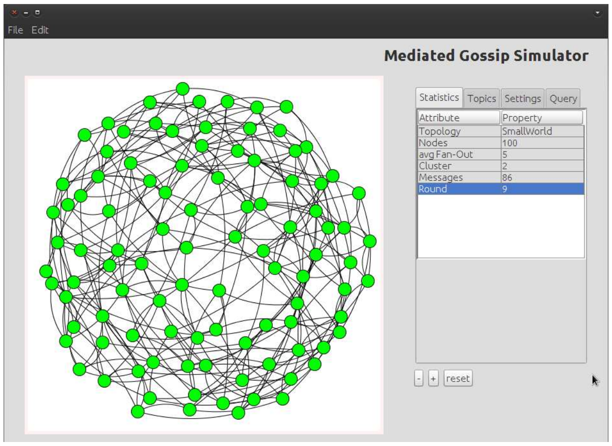

Fig. 4. Gossiping Simulation Software

TABLE II
PERFORMANCE OF DETERMINISTIC GOSSIPING IN DIFFERENT TOPOLOGIES

Topology:	avg Fan-Out	Messages	Rounds
2D Mesh	3	86	9
Small World	2	101	10
Power Law Distributed	4	86	9

Table 2 summarises the results of the proposed deterministic gossiping mechanism in different network topologies. As the results show in an average fan-out for each node, the performance gain achived can be evaluated using the results shown in Figure 2 and 3.

V. Conclusions and Future Work

This paper discusses a mediated gossiping mechanism to disseminate events and query data in large-scale sensor networks. We focus on scenarios that the exact nodes are not known in responding to a data query and also when a query is propagated through an overlay network of peer-to-peer gateways. The sensor observation and measurement data is published in relation to different context concepts. The query forwarding and data discovery is then performed according to the relevant topics. The mediated gossiping mechanism provides efficient G2G communications and reduces the number of messages while attempting to minimise the access time. In the capillary networks a similar mediated gossiping is introduced to forward the observed event (i.e changes in the environment) and/or data updates through multi-hop communications. The proposed solution is in particular helpful when there are large number of sensor nodes in the network and data is mainly provided via multi-hop access and gateway communications. The evaluation shows that the proposed mechanism performs better than probabilistic and flooding mechanisms.
In this work, we assume that queries are provided with relation to topics and we explore an abstract model (see Figure 1) to describe the logical grouping and overlay networks. The future work will focus on query pre-processing to identify the possible related topics to a query. Definition of topics and semantic structure hierarchies is also another issue that will be investigated in the future work.

Acknowledgment

This work has been performed in the framework of the ICT project ICT-5-258512 EXALTED, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues, although the views expressed are those of the authors and do not necessarily represent the project. This information reflects the consortium's view, the Community is not liable for any use that may be made of any of the information contained therein.

References

[1] OECD, "Smart sensor networks: Technologies and applications for green growth," December 2009, http://www.oecd.org/dataoecd/39/62/44379113.pdf.
[2] A.-M. Kermarrec, L. Massoulié, and A. J. Ganesh, "Probabilistic reliable dissemination in large-scale systems," *IEEE Trans. Parallel Distrib. Syst.*, vol. 14, pp. 248–258, March 2003. [Online]. Available: http://dx.doi.org/10.1109/TPDS.2003.1189583
[3] F. Ganz, P. Barnaghi, C. Francois, and K. Moessner, "Context-aware management for sensor networks," in *the Fifth International Conference on COMmunication System softWAre and middlewaRE (COMSWARE11)*, 2011.
[4] B. Pittel, "On spreading a rumor," in *SIAM Journal on Applied Mathematics*, 1987.
[5] C.-L. Fok, G.-C. Roman, and C. Lu, "Agilla: A mobile agent middleware for self-adaptive wireless sensor networks," *ACM Trans. Auton. Adapt. Syst.*, vol. 4, pp. 16:1–16:26, July 2009. [Online]. Available: http://doi.acm.org/10.1145/1552297.1552299
[6] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "Tinydb: an acquisitional query processing system for sensor networks," *ACM Trans. Database Syst.*, vol. 30, pp. 122–173, March 2005. [Online]. Available: http://doi.acm.org/10.1145/1061318.1061322
[7] K. Aberer, M. Hauswirth, and A. Salehi, "A middleware for fast and flexible sensor network deployment," in *Proceedings of the 32nd international conference on Very large data bases*, ser. VLDB '06. VLDB Endowment, 2006, pp. 1199–1202. [Online]. Available: http://portal.acm.org/citation.cfm?id=1182635.1164243
[8] S. Bandyopadhyay, M. Sengupta, S. Maiti, and S. Dutta, "A survey of middleware for internet of things," in *Recent Trends in Wireless and Mobile Networks*, ser. Communications in Computer and Information Science, A. zcan, J. Zizka, and D. Nagamalai, Eds. Springer Berlin Heidelberg, 2011, vol. 162, pp. 288–296. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-21937-5_27
[9] E. Souto, G. Guimarães, G. Vasconcelos, M. Vieira, N. Rosa, C. Ferraz, and J. Kelner, "Mires: a publish/subscribe middleware for sensor networks," *Personal Ubiquitous Comput.*, vol. 10, pp. 37–44, December 2005. [Online]. Available: http://dx.doi.org/10.1007/s00779-005-0038-3
[10] A. D. D. Kempe, J. Kleinberg, "Spatial gossip and resource location protocols," in *33rd ACM Symposium on Theory of Computing*, 2001.
[11] S. Voulgaris, A.-M. Kermarrec, and L. Massoulie, "Exploiting semantic proximity in peer-to-peer content searching," in *Distributed Computing Systems, 2004. FTDCS 2004. Proceedings. 10th IEEE International Workshop on Future Trends of*, may 2004, pp. 238 – 243.
[12] A. A. Abbasi and M. Younis, "A survey on clustering algorithms for wireless sensor networks," *Computer Communications*, vol. 30, no. 14-15, pp. 2826 – 2841, 2007, network Coverage and Routing Schemes for Wireless Sensor Networks. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0140366407002162
[13] R. Parshani, S. V. Buldyrev, and S. Havlin, "Critical effect of dependency groups on the function of networks," *Proceedings of the National Academy of Sciences*, 2010. [Online]. Available: http://www.pnas.org/content/early/2010/12/28/1008404108.abstract
[14] M. Lin, K. Marzullo, and S. Masini, "Gossip versus deterministic flooding: Low message overhead and high reliability for broadcasting on small networks," La Jolla, CA, USA, Tech. Rep., 1999.