Ad Hoc Networks 46 (2016) 61–74

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Gravity gradient routing for information delivery in fog Wireless Sensor Networks

Stepan Ivanov[a,*], Sasitharan Balasubramaniam[b], Dmitri Botvich[c], Ozgur B. Akan[d]

[a] Telecommunication Software and Systems Group (TSSG), Waterford Institute of Technology, Waterford, Ireland, X91 P20H
[b] Department of Electronic and Communication Engineering, Tampere University of Technology, Korkeakoulunkatu 3, Tampere, Finland, FI-33720
[c] LIGM Lab, University Paris-Est, Bât Copernic, 5, bd Descartes, Champs sur Marne, Marne-la-Vallé, France, 77454 Cedex 2
[d] Department of Electrical and Electronics Engineering, Koc University, Rumeli Feneri Yolu, Sariyer, Istanbul, Turkey, 34450

ARTICLE INFO

Article history:
Received 8 January 2016
Revised 22 March 2016
Accepted 24 March 2016
Available online 2 April 2016

Keywords:
Fog Computing
Wireless sensor networks
User-awareness

ABSTRACT

Fog Computing is a new paradigm that has been proposed by CISCO to take full advantage of the ever growing computational capacity of the near-user or edge devices (e.g., wireless gateways and sensors). The paradigm proposes an architecture that enables the devices to host functionality of various user-centric services. While the prospects of Fog Computing promise numerous advantages, development of Fog Services remains under-investigated. This article considers an opportunity of Fog implementation for Alert Services on top of Wireless Sensor Network (WSN) technology. In particular, we focus on targeted WSN-alert delivery based on spontaneous interaction between a WSN and hand-held devices of its users. For the alert delivery, we propose a Gravity Routing concept that prioritizes the areas of high user-presence within the network. Based on the concept, we develop a routing protocol, namely the Gradient Gravity Routing (GGR) that combines targeted delivery and resilience to potential sensor-load heterogeneity within the network. The protocol has been compared against a set of state-of-the-art solutions via a series of simulations. The evaluation has shown the ability of GGR to match the performance of the compared solutions in terms of alert delivery ratio, while minimizing the overall energy consumption of the network.

1. Introduction

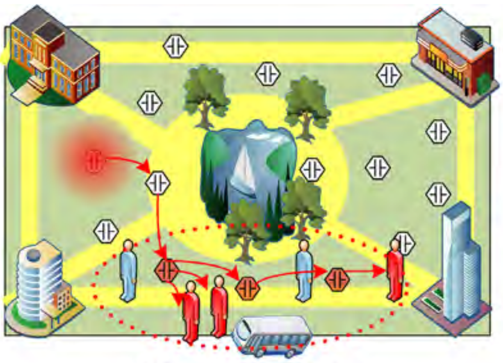
Popularity of Wireless Sensor Networks (WSNs) has been constantly increasing over the past number of years. Nowadays, WSNs could be found in most of the modern indoor and outdoor locations, where WSNs support a wide variety of applications. It is expected that this growth will continue, and, in the near future, multipurpose WSNs will be deployed everywhere. To sustain this, performance improvements will be required at all layers of WSN architecture, including the design of wireless sensor devices, their communications and applications. Although the capacity of a modern WSN today allows for certain complex tasks (e.g., data fusion), the improvements will continue to increase computational power of the WSNs, their efficiency and autonomy of operation. To take full advantage of the increase, CISCO have recently proposed the concept of Fog Computing [1], where services are proposed to be hosted (at least partially) by near-user devices (e.g., wireless sensors, gateways). The concept offers a number of advantages, including increased reaction time, sustainability and user-awareness. However, for the concept to be accepted by the general population, a critical mass of Fog Services need to be rolled-out. In this article we consider a possible Fog implementation of WSN Alert Services.

Typically, operation of a WSN does not imply direct interaction with the user. Monitoring data collected by the network is forwarded via a set of dedicated getaways to a cloud. On the cloud the data are processed and analyzed by an appropriate service that, if required, alerts the user. For example, based on results of WSN monitoring, asthmatics patients may be alerted of dangerously high pollen and pollution levels. However, transmitting information from sensors to the cloud requires additional resources (e.g., continuous Internet connectivity) lack of which may potentially delay alerting the user. As an alternative, certain analysis of the monitoring data can be carried out by the wireless sensors, while alerts detected as a result of the analysis can be handed-off to the user's hand-held devices (e.g., smart phones) directly by the sensor nodes. In this way, alerts will be delivered to the users spontaneously (i.e., on occurrence). This creates an opportunity for a WSN-based Fog implementation of Alert Services.

---

* Corresponding author. Tel.: +35351834022.
E-mail addresses: sivanov@tssg.org (S. Ivanov), sasi.bala@tut.fi (S. Balasubramaniam), dbotvich@gmail.com (D. Botvich), akan@ku.edu.tr (O.B. Akan).

http://dx.doi.org/10.1016/j.adhoc.2016.03.011



(a) Working time

(b) Lunch time

Fig. 1. Fog implementation of a WSN Alert Service: Application scenario. The alert delivery changes following the change in user-presence within the environment. The change can be seen between (a) working time, and (b) lunch time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this article we focus on a particular application scenario, illustrated in Fig. 1. The scenario includes a dense multi-purpose WSN, the *Sensor Environment* (*SE*). Each sensor is allocated a monitoring task and generates alerts on occurrence of specific events. Alerts are delivered to the users with regards to their preferences in order to avoid potential loss of user-interest. Based on the similarity of preferences the users are organized into groups, and group-based presence of the users is used to guide the alert delivery process. Thus, an alert, generated within the environment is initially delivered to a sub-set of intermediate sensor-nodes, located in vicinity of users from appropriate groups. Selection of these nodes will vary depending on the type of the alert (blue or red on Fig. 1) and time of its generation (lunch or working time). Once received by the intermediate nodes, the alert is handed-off to the devices of the users themselves. Depending on user presence, any sensor may become an intermediate node and act as a gateway for the users. In other words, a user's device that comes into close range of a sensor will receive spontaneous alerts from the WSN. We consider events that may engage simultaneously a number of sensors, which will generate similar alarms. Such alarms will be detected and fused together by the SE in order to achieve greater usability.

For the considered application scenario, achieving maximal performance efficiency will require solving a number of multi-disciplinary problems, such as: (I) gaining a deep understanding of user-groups and their mobility pattern, (II) developing efficient mechanisms of alert-detection, (III) optimizing alert delivery within the SE, and finally, (IV) developing alert fusion and hand-off to the users. Some of the problems have already been considered in other research. For example, user-group formation and mobility (Task (I)) is commonly considered by Social Network Analysis (e.g. [2–4]). Edge Mining [5] has been proposed for sensor alert detection (Task (II)). In this article, alert delivery within the SE (Task (III)) presents the focal point, where the main contributions include:

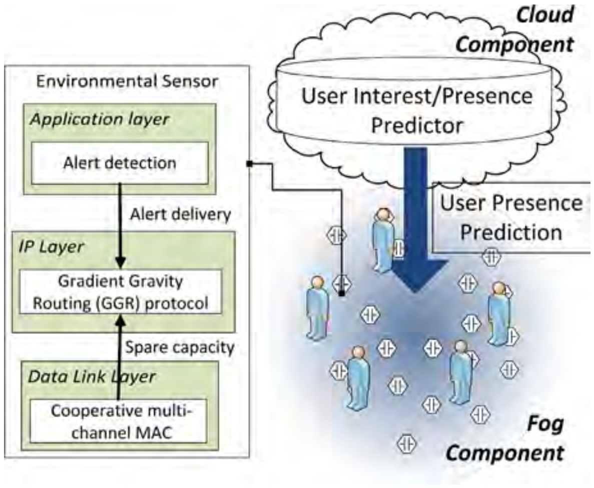


Fig. 2. Overall cross-layer architecture of the proposed user-group aware Sensor.

- Gravity Concept for user-group aware delivery of alert-based information in an SE. The concept takes into account group mobility of the users of the SE. The delivery prioritizes areas of the SE with higher user-presence, and is carried out in a fully distributed fashion that supports alert fusion.
- A user-group aware multicast routing protocol, namely the *Gradient Gravity Routing* (*GGR*) protocol is proposed. The protocol is based on the Gravity Concept and insures resilience to potential sensor-load heterogeneity across the SE (e.g., due to user-to-user traffic).
- Extensive simulation work that combines both real and synthetics traces of user mobility. The evaluation through the simulations compares the multicast routing protocols with well known protocols, as well as analyses the energy utilization of the sensor devices, average delivery ratio, forwarding rate, as well as the average delay.

The remainder of the paper is organized as follows: Section 2 present our vision of the Fog WSN Alert Service's architecture. Sections 3 and 5 describe in detail the Gravity Concept, the GGR solution and its validation. Section 6 provides an overview of the related work, and lastly Section 7 concludes the paper.

2. Alert service architecture

Despite the improvement in the design of wireless sensors, their capability remains insufficient for some of the tasks (e.g., user group analysis) identified earlier. To accommodate such tasks the SE architecture (Fig. 2) incorporates a dedicated cloud component. However, compared to the conventional design, responsibilities of the component are significantly reduced, due to the functionality shift towards the Fog component of the architecture.

Cloud component: Potentially large number of the SE users and memory limitations of the sensors significantly restrict user information that can be collected by the WSN while interacting with the users. Limited user information may indeed be insufficient to gain a full understanding of the user-behavior. Meanwhile, personal information may be available from various sources external to the SE (e.g., social-networking sites). Careful analysis of this information enriched with high-grained information provided by the user-devices (e.g., GPS-based mobility tracking) even though requires a powerful cloud infrastructure, can provide deep understanding of the SE users. This understanding can, in turn, significantly improve the performance of the SE. Therefore, the Cloud Component of the architecture has been introduced to host functionality of the *User Interest/Presence Predictor*. Major tasks of the predictor include, user profiling, group identification, and finally forecasting user-group mobility and consequently interest areas within the SE. The predictor will periodically (e.g., daily) receive all necessary behavioral information directly from the users' mobile devices as well as external sources and pass to the SE sensor predictions for the next period. In this way operation of the SE will not heavily rely on continuous high speed connectivity to the Cloud Component. The predictions passed to the SE represent a configuration of its operation for the next period. Each sensor will be supplied with a non-negative value reflecting on the user-presence in the sensor's transmission range. The predictions will be made for time-intervals of a fixed duration (e.g., one hour) on a per-group basis.

Fog component: The Fog component of the architecture is represented by the environmental sensors and their tasks. At the application layer each sensor hosts a monitoring functionality that detects specific events within the environment and generates appropriate alerts. The alerts are further multicasted to the other SE nodes with respect to the user-presence prediction. The multicast process is defined by the GGR protocol (see Section 4) located at the IP Layer. During the multicasting, alerts generated due to the same event are fused together. Any SE node receiving the alert (including the sensor that originated the alert) will also announce it to the SE users that are within close range. The GGR routing protocol utilizes the proposed Gravity Concept (see Section 3). In order to cope with the load-heterogeneity across the SE, the GGR incorporates an estimation mechanism for the spare channel-capacity at the Data Link layer. The mechanism requires a cooperative MAC protocol similar to the CAM-MAC-ARCB [6]. Therefore, the routing process is cross-layered incorporating both the gravity routing at the IP layer, as well as the spare channel-capacity estimation at the Data Link Layer.

3. Gravity concept

The Gravity Concept is one of the key contributions of the article and serves as a theoretical foundation of the proposed Gradient Gravity Routing protocol. The concept allows efficient fully distributed alert delivery within Sensor Environments, which connectivity graphs satisfy requirements of convex representability on compact (also introduced here). Prior to describing the Gravity Concept itself we would like to present the terminology used in this paper. The terminology includes notation for the WSN, the Fog component of the SE, as well as user-presence predictions casted by the User Interest/Presence Predictor.

Network: We consider the SE in the form of the connectivity graph $N = (S, L)$ of its sensors. Nodes S represent the sensors, while wireless links between them are represented by edges L. So, N is a finite directed graph that is also assumed to be connected. We denote the hop-count distance between the sensors s_1 and s_2 as $H(s_1, s_2)$.

User presence: In this section we consider SE users that belong only to a single user-group. We represent presence of the users of the group as a non-negative weight function $W(\cdot)$. The function is defined on the node-set S, where for each sensor $s \in S$ the value of $W(s)$ equals to the expected user-presence within the sensor's transmission-range. We deliberately neglect evolution in time of the user presence, as we assume its evaluation speed to be significantly lower than the expected rate of alert-packet exchange between sensors. This assumption comes from the highly-restricted storage-capacity of the environmental sensor. Only a limited information on user-presence prediction may be stored by each sensor. Thus, user-presence predictions made on hourly (or other) basis are assumed to be available.

For an alert forwarded by a particular sensor $s' \in S$, the cumulative network distance towards sensors from a sub-set $S^* \in S$ with respect to their expected user-presence values is defined as:

$$D_{S^*}(s') = \sum_{s_i \in S^*} W(s_i) \cdot H(s_i, s').$$

The expected user-presence values reflect on the number of users expected within the transmission ranges of the sensors from S^*. Therefore, $D_{S^*}(s')$ reflects the cumulative distance from the alert to those users. Hence, if there is a sensor $s'' \in S$ that $D(s') > D(s'')$, then forwarding the alert from s' to s'' potentially brings it closer to all those users simultaneously. Consequently, as N is finite and contains only a finite number of nodes, $D_{S^*}(\cdot)$ reaches its global minimum at least at one sensor, closest to the users. This allows us to formulate the following definition:

Definition. For an SE connectivity graph $N = (S, L)$, a sensor-weight function W, and a sensor-subset S^* of the graph, a node $s^* \in S$ where $D_{S^*}(\cdot)$ (function representing the cumulative distance towards the sensor-subset S^*) reaches its global minimum, is referred to as the *Gravity center* (*GC*) of the subset S^*.

As N is finite by definition, for any W, and S^* we can guarantee existence of a GC sensor. Meanwhile, in certain cases the $D_{S^*}(\cdot)$ may reach the global minimum at a number of sensors (e.g., N is a dumbbell-graph with two nodes with equal weights), leading to existence of multiple GC sensors. Next we present another important property of a GC sensor:

Proposition 1. *For an SE connectivity graph $N = (S, L)$ and a sensor-weight function W, consider a GC sensor s^* of a non-trivial sensor-subset $S^* \in S$ (consists of two or more sensors). In this case, S^* contains at least two sensors s_1 and s_2 such that no shortest path from s_1 to s^* contains an intermediate sensor s^{**} that also belongs to a shortest path from s_2 to s^*.*

Proof. The proposition is proven by contradiction. If the proposition does not hold true for a particular case, then N contains a sensor s^{**} such that all sensors of S^* were connected with s^* via shortest paths going through s^{**}. Thus, for $\forall s \in S^*$: $H(s^{**}, s) < H(s^*, s)$ resulting in $D_{S^*}(s^{**}) < D_{S^*}(s^*)$, which contradicts s^* being a GC sensor. □

Proposition 1 guarantees that nodes of any non-trivial sensor-subset S^* can be divided by any of its gravity centers (s_*) into two or more sub-subsets, where each sub-subset will include sensors that share the same next hop towards the GC center s^*. Note that if the gravity-center s^* belongs to the S^*, then one of the sub-subsets will consist only of the s^* sensor. In this way, Proposition 1 describes an iterative process that constructs a sensor-subset hierarchy from the original subset S^*, where division of a parental subset over one of its gravity centers forms subset of the next level. Meanwhile, the gravity centers used during the process also present a hierarchy that we call the *Gravity Hierarchy*. The iterative process stops when each leaf-subset of the hierarchy contains only a single sensor that also is the GC of the leaf-subset. Consequently each sensor of the original subset S^* is included at least once into the Gravity Hierarchy. We propose the Gravity Hierarchy to be used for alert multicasting. Next we concentrate on developing an effective GC search-algorithm. We consider connectivity graphs with a certain property, namely *convex representability on compact*. The definition uses mathematical concept of a compact set, or *compact* and a convex function. Compact is a set that is closed and bounded. Examples of compacts include closed intervals and rectangles. Compacts have a set of useful properties, especially in relation to convex functions. Information on that can be found, for example, in [7]. One of this properties is exploited further in this article. The definition considers existence of a possibility to assign sensors-nodes to elements of a compact C, where the assignment itself is denoted as a function Im: $S \to C$. The definition itself is as follows:

Definition. Let the SE connectivity graph $N = (S, L)$ be of such a type that for a compact C each sensor $s' \in S$ can be assigned an element of the compact ($Im_C(s') \in C$) so that there is a convex function $H_{s'}$ defined on the compact C such that the hop count distance from s' to any other node $s'' \in V$ equals to $H_{s'}(Im_C(s''))$. We call such graphs *convex representable on compact*.

Convex representability on compact of the SE connectivity graph N significantly simplifies the gravity center search. This is justified by the following proposition:

Proposition 2. *Consider an SE connectivity graph $N = (S, L)$ that is convex representable on compact, and a non-negative sensor-weight function W. For any sensor-subset $S^* \in S$ a GC can be found by an algorithm that traverses through the sensors of the graph following a decrease of the accumulative network distance D_{S^*} function. The algorithm stops at a GC of the sensor-subset S^* regardless of the starting point.*

Proof. As N is convex representable on compact, there is a compact C such that for any $s^* \in S^*$, the hop count distance to any other $s \in S$ equals to $H_{s^*}(Im(s))$. H_{s^*} is a convex function defined on the compact C. Hence, for any sensor $s \in S$ the value $D_{S^*}(s)$ is equal to:

$$D^*_{S^*}(Im(s)) = \sum_{s_i \in S^*} W(s_i) \cdot H_{s_i}(Im(s)).$$

As W is a non-negative weight function, $D^*_{S^*}$ is also a convex function on the compact C. Meanwhile, the existence of a local minimum for $D_{S^*}(s)$, that is not a global minimum, would indicate the same for $D^*_{S^*}$ on C. This would contradict $D^*_{S^*}$ being a convex function on C, as any local minimum of a convex function is also the global minimum. Consequently, the global minimum of D_{S^*} can be found by a gradient search regardless of its starting point, as any of D_{S^*} local minimums is also a global minimum. This proves the proposition. □

Propositions 1 and 2 present the overall concept of our proposed multicast routing algorithm that is the foundation of GGR. Thus, in order to deliver an alert to sensors of a subset S^*, a sensor forwards the alert following the decrease of this subsets D_{S_*} function. Once the forwarding reaches a GC of the subset, the subset is divided in accordance to Proposition 1 and the alert delivery is commenced for each of the subsets individually. Furthermore, Proposition 2 also shows that Gravity Routing concept possesses a significant potential and need for data-fusion. Thus, the delivery routes for alerts are identified with regards to their receivers (the subset S^*) as well as the originating sensor. Therefore, alerts intended for same receivers will be delivered via the same subset of GCs. Consequently, these GCs will be in position to fuse these alerts if they are related to identical events, and, therefore, reduce traffic forwarding within the SE.

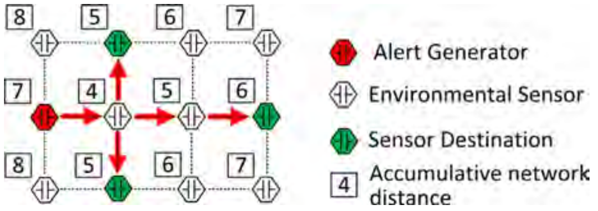


Fig. 3. An illustration of the Gravity Routing concept for a single alert to three destination sensor nodes.

Meanwhile, Proposition 2 limits the scope of SE topologies that the concept is applicable to, as the SE connectivity graph is required to be convex representable on compact. One example of an acceptable SE is a regular $N \times M$ sensor grid, where the grid step is equal to the sensor transmission range. Each sensor s^* of the SE can be assigned a pair of its own grid coordinates ($x(s^*)$, $y(s^*)$), that is also an element for compact $C = [1; N] \times [1; M]$. Consequently, the network hop-count distance from the sensor s^* to any other sensor s equals:

$$H_{s^*}(x(s), y(s)) = |x(s^*) - x(s)| + |y(s^*) - y(s)|,$$

which is a convex function on C. An example of an alert multicasting within such an SE is illustrated in Fig. 3. An alert is multicasted to a subset of three sensors with weights equal to 1. The original sub-subset is divided into three at its GC (convex value equals 4), whilst further packet forwarding aims at each sensor-destination individually.

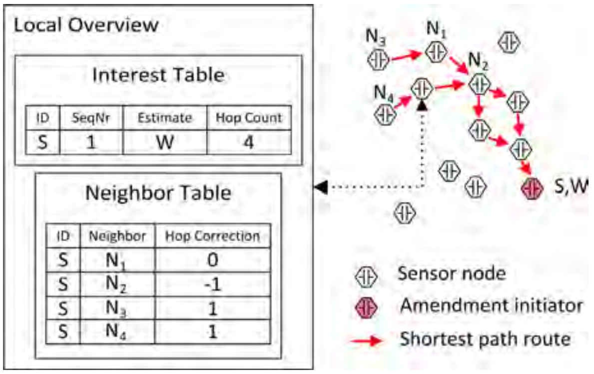
4. Gradient gravity routing

The proposed GGR protocol is based on the GC presented in the previous section. The protocol incorporates two independent processes carried out by the SE sensors. In the first process, the *User Interest Dissemination* (*UID*) raises awareness across the SE of the expected user-presence within the SE, as predicted by the User Interest/Presence Predictor. In the second process, the Adaptive Alert Multicasting delivers alerts within the SE regarding the user-presence values predicted for its sensors. The following description presents both of the processes. Initially the description considers only a single group, while a generalization is provided later for the cases of multiple user-groups and application domains other than WSN Alert Services.

4.1. User interest dissemination

The purpose of the UID process is to enable each environmental sensor to provide other SE nodes with hourly updates (Fig. 4) on its presence values predicted by the User Interest/Presence Predictor. The updates are periodically diffused by the sensor across the environment. This allows the sensor to form their *Local Overviews* of the SE by observing the UID processes of each other. Each sensor stores its overview internally, where the overview consists of the “*Interest*” and “*Neighbor*” tables.

The Interest Table 1 holds the user-presence values received from other sensors and has the following fields: *IP address*, *last update SeqNr*, *user-presence value*, and *hop-count*. Initially, the table is empty, and its content is filled in/modified each time the sensor receive a new update. Sensors of the SE, whose IP addresses are not present in the table are assumed to have 0 user-presence. The contents of the Interest table enable the sensor to calculate its



Interest Table

ID	SeqNr	Estimate	Hop Count
S	1	W	4

Neighbor Table

ID	Neighbor	Hop Correction
S	N_1	0
S	N_2	-1
S	N_3	1
S	N_4	1

Fig. 4. The local overview tables within a sensor node that contains the *Interest* and *Neighbor* tables.

Table 1
Simulation parameters.

Transceiver: CC 2420, Transmission rate 0.2 Mbps,
Range: 25ft, 1 Control Channel, 3 Data channels

Power consumption: Transmission (33 mW),
Reception (56.4 mW), Idle (1.27 mW), Sleep (0.06 mW)

Environment: 96 sensors, grid topology; User-groups: 4
Area: ((1698300.0; 259947.0) (1698600.0; 260347.0))
Events: 1 min., 1pkt/s, 100 bytes/pkt
Simulation time: 24 h; Averaging: 20 runs

own cumulative network distances D_{S^*} for any sensor-subset S^* of the SE.

The Neighbor table stores information that allows the sensor to identify the hop-count distance from each of its immediate neighbors to any sensor from the Interest table. So, for each neighbor–sensor pair the table keeps a hop count correction that indicates whether the neighbor is either 1 hop further/closer or at the same distance to the sensor. The contents of the two internal tables allows the sensor to calculate cumulative network distances for any of its immediate neighbors.

Packet exchange associated with the UID process represents an operational overhead of the GGR protocol, as it is only subsidiary but not alert-related information that is carried out by the packets. Indeed, the UID process may be rather resource-consuming for the SE update-diffusion operation, and local views of the sensors may be large in size. However, such an operation is necessary for truly targeted information delivery. Thus, any node of the SE may generate an alert, where the delivery will require information regarding the user-presence within the SE. Furthermore, the extent of update-diffusion involvement and the size of local views will vary depending on the SE activity. For example, in cases when user-presence within the environment does not vary significantly (e.g. people constantly present/working in a room/office during day-time), the usage and the impact of the diffusion operation will be limited. Similarly, local views of the sensor nodes will be smaller in cases when user-presence within the SE is noticeably clustered. The UID overhead will become apparent when user-presence is spread across the SE, and density of the presence varies rapidly.

4.2. Adaptive alert multicasting

The adaptive alert multicasting operates assuming that the foregoing UID process has completed and the local network view of each individual sensor agrees with the global picture. Therefore, each sensor, while generating an alert, provides it with the list of intended receivers. The list is generated based on the local overview of the sensor, including only nodes with positive user-presence values. The alert is multicasted by the network sensors according to the GC concept presented earlier. Intended receivers encountered during the multicasting are deleted from the alert's list.

The adaptive alert multicasting is composed of the two following operations: **gradient gravity forwarding** and **route branching**. Algorithm 1 presents a Java-based pseudo-code of the GGR algorithm. To forward an alert towards a set of intended receivers an SE node initially, based on its local overview, establishes if the node is a GC for the set. If not a center, the alert is further forwarded towards a GC. The forwarding adapts to possible load heterogeneity within the sensor environment, as presented below. The route branching operation is carried out if the node is a GC. The list of the alert's intended receivers is divided into a number of sub-lists on the next-hop basis, as explained above. The division is carried out using the Neighbor table of the SE node. The alert is further forwarded towards the formed sub-lists.

While the ability of this multicasting algorithm to reach all intended receivers has been shown earlier, complexity of the algorithm also requires a consideration. The complexity will significantly depend on the activity of the SE users, as the alert traffic is formed within the SE with respect to the user-interest predictions. For example, in case when all of the user-interest at a particular time-interval is concentrated within proximity of one node, the shortest route will be chosen for each alarm generated within the SE. In case when user-interest is split between two nodes, the delivery will first target the GC of these nodes and then each node individually. This will require additional alert forwarding within the environment, which will increase the complexity of the algorithm's operation in this case. The extent to which operation will be affected is a complex question. In this article, this question is considered in Section 5 based on the simulation results.

4.2.1. Gradient gravity forwarding

The presence of unicast user traffic (user-to-user communication), as well as heterogeneity of alert traffic from the sensors (e.g., video surveillance traffic and temperature measurements), will lead to network load variation within the SE. In such a case, forwarding the alert through highly loaded regions of the SE may affect its delivery to a GC and further to the intended receivers. In order to tackle this issue, the proposed solution uses gradient-based route adaptation technique that avoids highly loaded regions of the network (Fig. 5(a)). The technique stretches across Data Link and IP layers as presented in Fig. 5(b). Thus, the Load Monitoring service located at the Data Link layer allows each network node to estimate routing capacity of itself and its immediate neighbors. The Load Monitoring service requires deployment of a cooperative

Algorithm 1 MultiCasting(Packet PKT).

```
PKT.exclude(this.id);
if Gravity center then
    if PKT list size $>$ 1 then
        Packet newBranchPkts[];
        newBranchPkts = RouteBranching(PKT);
        for branchPkt $\in$ newBranchPkts do
            Forward(branchPkt);
        end for
    else
        Forwarding is complete;
    end if
else
    nextHop = GetNextHop(PKT);
    ForwardTo(PKT, nextHop);
end if
```

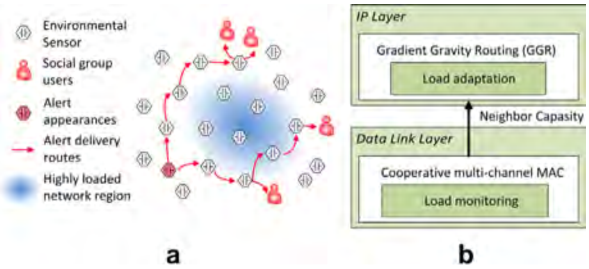


Fig. 5. Illustration of the adaptive routing mechanism in the GGR: (a) Routing around high network load regions with different priority and (b) architecture of the cross-layer cooperation.

MAC protocol similar to the CAM-MAC-ARCB [6]. The Routing Capacity estimations are further fed to the IP layer, where the routing process determines the path by creating a gradient field within the environment. Therefore, at each node i of the network the gradient field $Gr_{n,\,S,\,n\,\rightarrow\,i}$ represents its capacity for forwarding the alert from its origin (n) to a GC of the intended receivers (set S) and is represented through the following equation:

$$Gr_{n,S,n\rightarrow i} = \gamma \cdot \Phi_i + (1-\gamma) \cdot \hat{D}_S(i),$$

where $\hat{D}_S(i)$ represents the cumulative hop count to S from node i, normalized with respect to the alerts origin; and Φ_i denotes the capacity of the node to forward packets. The Φ_i values are obtained by the Data Link Load monitoring services. The normalized cumulative hop count is represented as follows:

$$\hat{D}_S(i) = (D_S(n) - D_S(i))/D_S(n),$$

where D_S is the cumulative hop count to S (Section 3). Note that Proposition 2 guarantees that $\hat{D}_S(i) \leq 1$ for any node i and has higher values for nodes with lower accumulative distance towards the set S. The routing process selects the path traversing through nodes with maximal gradient field values in order to increase chances of arriving at a GC. Therefore, $\gamma \cdot \Phi_i$ is a linear load-based correction of the gravity-based path, where parameter γ represents reactivity of the established routes and determines how far routes may divert while avoiding highly loaded regions of the network.

4.2.2. Data fusion

A problem with every sensor delivering alerts into the SE is the increased traffic on the network, which in turn will lead to high energy consumption. Therefore, integration of a data fusion process for the multicast communication will lower the load across the SE. Meanwhile, as our proposed Gravity Routing concept possesses a significant potential for fusion, using an appropriate data fusion technique together as part of GGR is particularly important.

Typically data fusion is driven by the type of sensor data that defines which packets and how they can be merged together. Nowadays a wide variety of fusion techniques are available for a wide range of sensor data stretching to multimedia and video [8,9]. In this article, we assume that only a simple fusion process is available to the environmental sensors. Each two alerts carrying correlated information (i.e. describe similar events brought to the attention of the same user-group) can be merged together. The result of this merging is a single alert that accumulates information from both of the original alerts. Such fusion is possible for various alarms indicating presence within the environmental areas with low/high humidity, atmospheric pressure, level of pollution. Suppose the alerts to be fused have S_1 and S_2 lists of intended receivers. These lists may differ depending on the sensor-origins of the alerts and their previous routes towards the node performing fusion. Since all nodes from the S_1 and S_2 lists require to receive information from both of the alerts, the receiver list of the fused alert should include nodes of $S_1 \cup S_2$. Hence, in order to describe compression degree of such a fusion we use the following *compression value* metric:

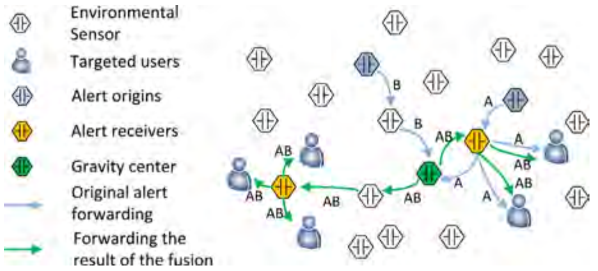


Fig. 6. Illustration of the data fusion process at the GC for the multicast alert.

$$Cmp = |S_1 \cup S_2|/(|S_1| + |S_2|).$$

The metric reflects reduction of the alert traffic within the environment and may take values from the interval [0; 1]. Fusions of higher compression degree have lower metric values.

Fig. 6 illustrates fusion of two correlated alerts originated from different environmental sensors. Alerts A and B are multicasted to the same set of sensors that further propagate these alerts to the users. Initially each of the alerts is propagated to the GC of the receivers, where the alert fusion is performed. Even though alert A is delivered to the GC via one of the receivers, the result of the fusion AB is propagated to both of the receivers.

4.3. Multiple user-groups and other applications

While the description of the previous subsection assumes existence of only a single user-group, transition to the case of multiple groups is presented here. The transition concerns the concept of multicasting rather than the proposed routing protocol.

The proposed solution treats users of each group independently and disregards interdependencies between their behavior/group mobility. Therefore, the UID operation is required to cater for all of the groups. Hence, the updates provided by the sensors are required to contain necessary information for all the groups. Another modification will concern the Interest tables that are required to reflect group information for the stored user-presence values. These modifications enable each sensor to calculate necessary D_S values for each alert for a number of social groups.

Even though, the GGR protocol is considered in this article solely in the context of a Fog implementation of WSN Alert Services, the protocol can be also easily adopted and applied in other domains. The GGR is effectively a multicast routing protocol that performs information delivery with respect to a certain quantitative measure (i.e. weight) associated with the network nodes. Thus, in order to apply the protocol to a particular domain, it is only the measure that needs to be adopted while the GGR dissemination and GGR multicasting processes may be used as presented in this article. The fusion component of the protocol will need to be developed regarding to the information exchanged within the network.

5. Simulation

In order to validate the proposed GGR protocol for Fog Alert Services, an extensive simulation work has been conducted on our Java-based event driven simulator. The simulation is divided into a number of subsections, which evaluate the proposed solution in comparison against other state-of-the-art multicast protocols and consider the adaptability of the alert delivery in the presence of user-to-user unicast traffic sent via the SE.

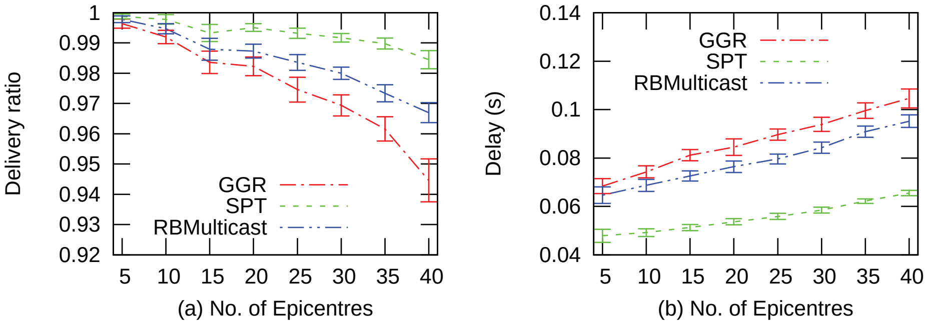


Fig. 7. Impact of varying the number of event epicenters on the (a) delivery ratio; and (b) delay.

5.1. Simulation setup

This section presents a detailed description of the simulation setup used for the evaluation. The overall simulation parameters are presented in the table above.

5.1.1. Environmental sensor network

As it has been presented above, our proposed solution is based on the Gravity Concept of multicasting that requires connectivity graph of the sensor environment to be convex representable on compact. Therefore, we consider a wireless sensor environment that consists of 96 sensors organized in a grid topology with step size equal to 7 m. Each of the sensors is equipped with a single CC 2420 transceiver. At the Data Link layer each sensor employs CAM-MAC-ARCB [6] due to its ability for spare channel-capacity estimation. In order to reduce the alert traffic each sensor is enabled to perform a sensor data fusion, that merges alerts related to the same event. We consider sensors to be of a multi-purpose nature, where each sensor may obtain environmental measurements. Based on these measurements, the sensors detect occurrence of specific events within the environment. Each hour one event relevant to one of the user-groups occurs.

Event structure: Each event considered during the simulation lasts for a duration of 1 min. We assume an event to have a number of epicenters uniformly distributed across the environment. All epicenters are of equal size M, where at each epicenter the event will be detected by M sensors nearest to the center. Each such sensor transmits alert packets of 100 bytes with 1 pkt/s frequency for the duration of the event.

5.1.2. User mobility

Using realistic activity logs for users is highly beneficial for the evaluation. Therefore, we derive user activities from the "*UCSD Wireless Topology Discovery Trace*" presented in [10]. The trace accumulates activities for a large amount of computer science students of the University of California, San Diego. The trace contains signal strength measurements for each student device obtained by various on-campus APs whose geographical locations are also supplied with the trace. This, in turn, allows us to approximate for each user device its location at any time t as the weighted average of the APs' coordinates with respect to the registered signal strength. Unfortunately, the trace does not reflect particular preferences of individual students; hence, these preferences are assigned randomly. Based on the assignment, the students are divided into four groups. The SE considered in the simulation is located within the geographical area with the following coordinates ((1698300.0; 259947)(1698600.0; 260347)). Each simulation run considers one of the days (24 h, 29th October 2002) that user information is logged in the UCSD trace.

5.1.3. Comparison of protocol performance

We compare our proposed routing protocol (GGR) against two of the previously proposed protocols for multicasting: *Shortest Path Tree* (*SPT*) and *RBMulticast* [11]. RBMulticast is a typical example of the geographical multicast approach. Each multicasted alert is forwarded in a hop-by-hop fashion. Each forwarding node groups the destinations of the alert based on their quadrants with respect to the node. The alert is forwarded towards geographical centers of these groups. The SPT protocol is widely used for multicast protocol evaluation. SPT presents a typical example of the structure-based multicast approach. Each alert is passed down a tree that consists of the shortest path connecting the source of the alert with the destination. The tree is built incrementally using the *Takahashi–Matsuyama* heuristic [12]. The GGR is presented above in Section 4. As γ parameter represents the reactivity (ability to divert traffic from highly-loaded parts of the network) of the GGR to external and unicast traffic, scenarios where such a traffic is absent use γ equal 0. The influence of γ is considered independently in the part of the evaluation that is dedicated to the adaptability of the solution.

5.2. Performance evaluation for varying number of alert epicenters

Fig. 7(a) and (b) presents results obtained for events with various number of epicenters of size 1. Events with a higher number of epicenters are detected by a larger number of sensors, which results in a larger amount of alert traffic propagated by the sensors towards users. The comparison of the three protocols show similar performances for a smaller numbers of epicenters. Meanwhile, the performances of all three protocols deteriorate with the increase of the number of epicenters. However, despite the deterioration, the protocols exhibit good performance, where even for the highest number of epicenters, the drop in the delivery ratio does not exceed 6%. Regarding the alert delivery ratio (Fig. 7(a)) and the delay (Fig. 7(b)), the GGR suffers the most from the increase, while the best performance is shown by SPT.

The reason for the behavior of the protocols demonstrated in Fig. 7(a) and (b) comes from the number of hops each protocol requires an alert to travel during its delivery (Fig. 8(a)). Thus, SPT selects the shortest paths towards the destinations and hence minimizes the number of hops. GGR and RBMulticast cluster the destinations and accomplish the delivery via the cluster centers. Therefore, GGR and RBMulticast require the alert to travel higher number of hops than SPT. Meanwhile, each destination cluster of GGR is further divided only at one of its centers, while in the case of RBMulticast such a division may occur earlier. Each division focuses the delivery on particular nodes and correspondingly corrects its route. Thus, early division makes the delivery more targeted and shortens its route. Hence, GGR makes the alert to travel a higher number of hops than RBMulticast. However, the high po-

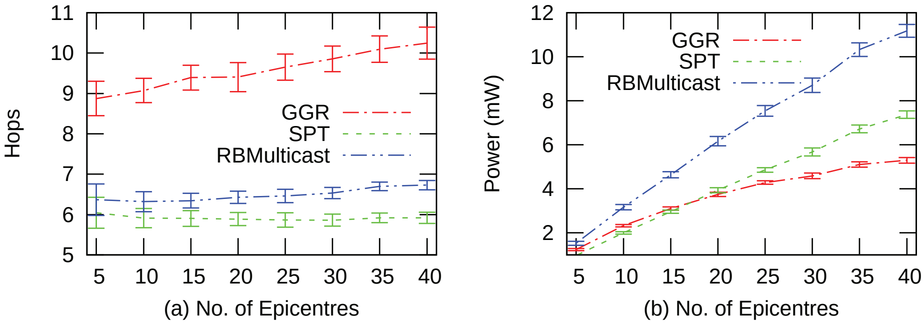


Fig. 8. Impact of varying the number of epicenters on the (a) hop count; and (b) network power consumption.

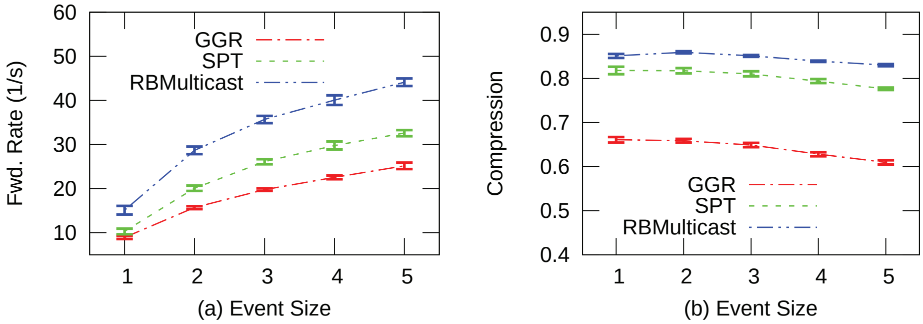


Fig. 9. Impact of varying the epicenter size on the (a) alert forwarding rate; and (b) fusion compression value.

tential of GGR for data fusion allows it to significantly reduce the energy expenditure of the environmental sensors. Thus, Fig. 8(b) shows that GGR has the least aggregated network power consumption (across all nodes of the SE) amongst the three protocols.

5.3. Data fusion performance

Next we present results on the impact that data fusion has on the performance of the protocols. The results are obtained for events with five epicenters of various sizes. Fig. 9(a) and (b) presents the comparison of the node compression values (Section 4.2.2) as well as the rates at which alert packets are forwarded (forwarding rate) by the sensor nodes. Increase of the epicenter size results in an increase of the number of the environmental sensors generating alerts. Delivery of an increased number of alerts requires an increased number of packets to be forwarded within the SE. Meantime, the increase is restrained by data fusion executed by the sensors (compression value decreases as shown in Fig. 9(b)). Therefore, GGR has the lowest forwarding rate due to its high potential for data fusion (lowest compression value). SPT experiences lower increases in the forwarding rates than RBMulticast again due to the differences in the length of the selected delivery paths. The growth in the event size has different effects on the performances of the protocols due to the inequality of the forwarding rate increase (Fig. 10).

5.4. Solution scalability

Figs. 11 and 12 present scalability study of the protocols. The study considers altering the size of the area covered by the SE. We consider only two alteration types: reduction and extension of the original area along the *Y*-axis. The alteration changes the amount of sensor of the environment but neither affects the distance between neighboring sensors nor their grid-like placement. Therefore, the altered environments still conform to the requirement of the Gravity Concept. The results are obtained for networks of 32–160 sensors, whereas all events have 25 epicenters of size 1. The figure shows that extension of the coverage area leads to a performance degradation observed for all three protocols. However, such a degradation is inevitable, since in larger SEs, information is expected to be further distanced from the users, and therefore its delivery requires longer routes (Fig. 11(a)). Meanwhile, the comparative performances of the protocols remain similar to the ones as observed previously. GGR requires a higher number of hops (Fig. 11(a)) for delivery and this slightly affects that delivery ratio (Fig. 11(b)). However, the potential of data fusion results in a lower forwarding rate for GGR (Fig. 12(a)), which results in a higher energy efficiency (Fig. 12(b)).

5.5. Adaptability performance

This part of the simulation evaluates the ability of our proposed solutions to adapt to various network heterogeneities that alert delivery may encounter. Since the essence of this ability is represented by the γ parameter of the GGR, the evaluation considers using various γ-values.

Fig. 13(a)–(c) presents results obtained for the case of events of 5–40 epicenters of size 1. Thus, the figures demonstrate delivery ratio and delay improvement resulted from using 0.2 and 0.4 γ-values in comparison to the 0.0 value. Limited number of nodes forming the gravity hierarchy utilized by the GGR may concentrate load in certain parts of the SE, and this may, in turn, affect the alert delivery process. Using a higher γ-value stretches the hierarchy across a lager set of network nodes, and therefore, achieves a better load balance across the network. This effect is more visible for events with a higher number of epicenters as they trigger a larger amount of alert traffic. However, due to the moderate rate of the alert traffic (even in cases of high event scales), the loss due to the heterogeneity of the alert forwarding traffic is also quite moderate. This explains relatively low gain values demonstrated by the figures. Meanwhile, the stretch increases the alert forwarding rate of the SE (Fig. 13(b)), which results in an increase of the network power consumption (Fig. 13(c)).

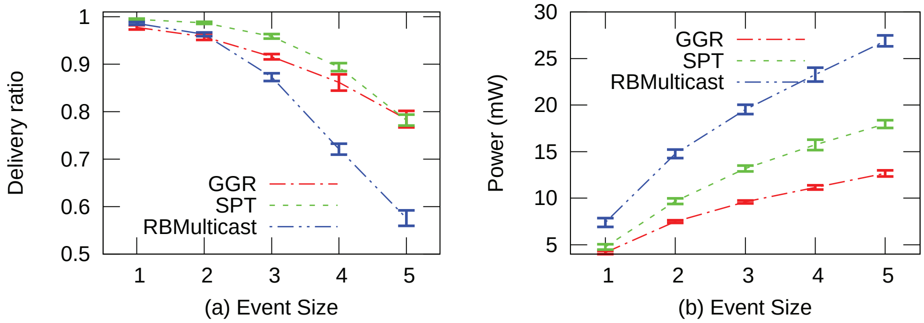


Fig. 10. Impact of varying the epicenter size on the (a) delivery ratio; and (b) network power consumption.

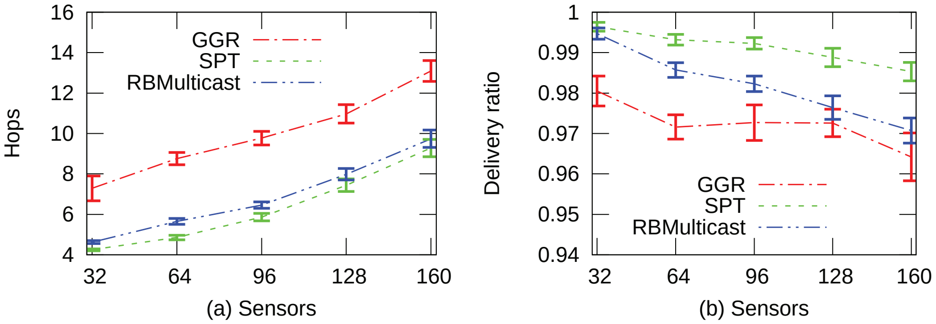


Fig. 11. Impact of varying the size of the sensor environment on the (a) hop count; and (b) delay.

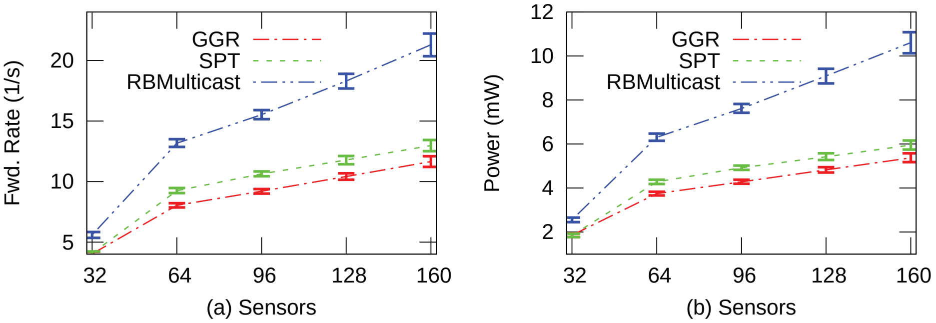


Fig. 12. Impact of varying the size of the sensor environment on the (a) alert forwarding rate; and (b) network power consumption.

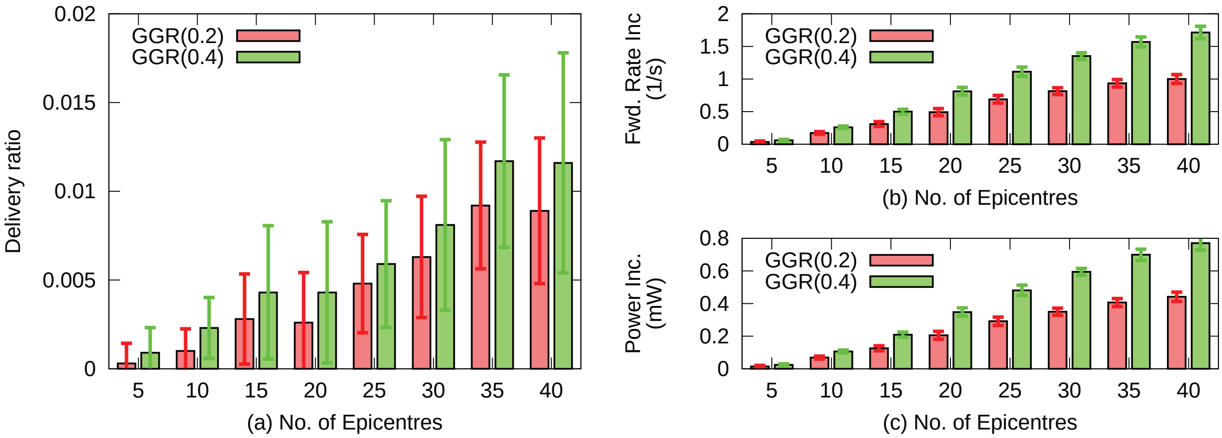


Fig. 13. Varying the quantity of the event epicenters for both the 0.2 and 0.4 γ-values, and its impact on the (a) alert delivery ratio increase; (b) alert forwarding rate increase; and (c) network consumption increase.

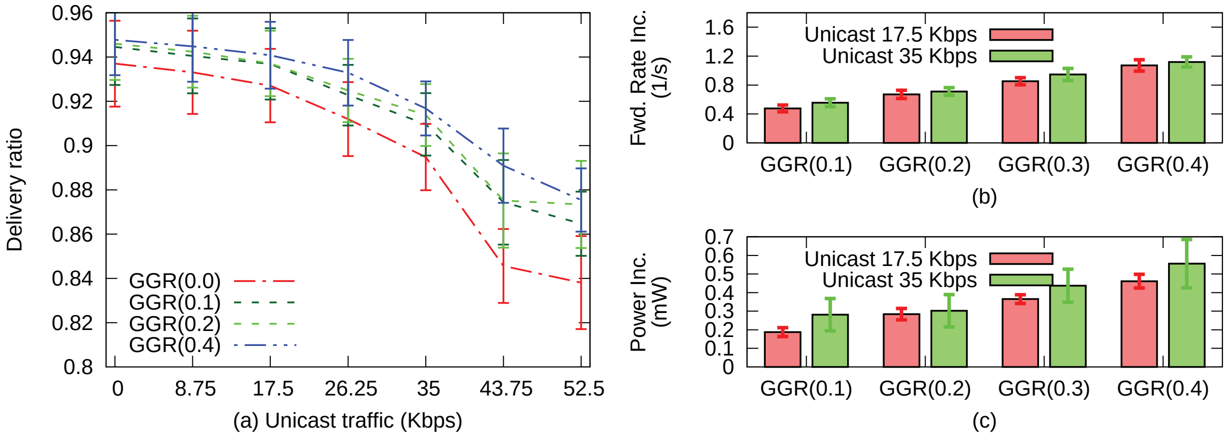


Fig. 14. Adaptation to the presence of unicast traffic, and its impact on the (a) alert delivery ratio; (b) increase in the alert forwarding rate; and (c) increase in network power consumption.

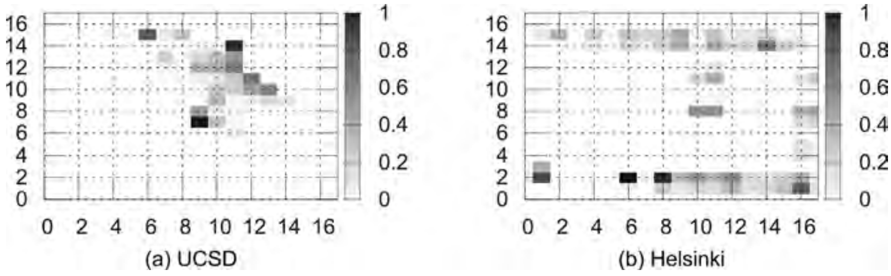


Fig. 15. User mobility patterns: (a) UCSD campus; (b) Helsinki city center.

Fig. 14(a)–(c) presents evaluation of the ability of our proposed solution to adapt to traffic heterogeneities that may occur within the environment due to the presence of unicast user-to-user communication. For that purpose, we consider alert delivery for events with 25 epicenters of size 1 in case of 1 unicast communication established. The communication involves packet exchange between two of the present users, that generate CBR traffic at rates between 0 to 52.5 Kbps each. Fig. 14(a) presents values for the alert delivery ratio in case of 0.0, 0.1, 0.2 and 0.4 γ-values utilized by the GGR. Using a higher γ-value increases reactivity to traffic heterogeneities of the alert multicasting and guides the packet forwarding process further away from highly loaded parts of the network. This results in the increase of the alert delivery ratio, as it is presented by the figure. However, it also results in a larger number of network nodes involved in the packet forwarding process, which consequently results in an increase in the sensor energy consumption. Thus, Fig. 14(b) and (c) shows the increases in forwarding rate and network power consumption resulting from using various γ-values in comparison to the 0.0 value, where the results correspond to 17.5 and 35 Kbps user-to-user unicast rates.

5.6. Effect of user behavior

The performance of an SE significantly depends on the behavior/group mobility of the users within the coverage area of the network, and this in turn will affect the Fog Alert Service performance. Thus, for an individual alert, its destinations and, therefore, the delivery routes are identified with respect to the user presence on per-group basis. These routes influence the overall performance of the SE. To provide an illustration for this effect, we compared performance of the three protocols for the main UCSD mobility trace against a trace that is artificially generated using *The One Simulator* [13]. The artificial trace models 24-h mobility of 100 individuals whose work-places are located within an area of the city of *Helsinki* limited by streets: *Fabianinkatu*, *Sofiankatu*, *Esplandi* and *Aleksaterinkatu*. The area is equipped with an 18X18 SE that alerts the users. Performance of the network is compared with an SE of identical-size deployed at the UCSD campus. While in other sub-sections we consider users of a number of groups, in this sub-section we consider users of only one group in order to simplify presentation of differences in their mobility for the two scenarios.

Fig. 15 presents normalized user presence density accumulated over the 24 h period (values equal to 1 correspond to most popular locations amongst the users). The figure clearly demonstrates difference between line-wise (i.e. city-street) geometry of user presence in Fig. 15(a) and campus-wise geometry presented in Fig. 15(b). Appearances of the users in the UCSD scenario have a more-pronounced cluster nature, while user-appearances in the Helsinki scenario are distributed along the streets within the considered area.

Figs. 16 and 17 present performance evaluation of the three protocols in the two scenarios. The evaluation compares results obtained for alerts generated for events with various number of epicenters of size 5. Due to the larger sizes of the SEs considered, in this sub-section we consider appearance of five concurrent events to increase visibility of various networking effects (i.e. link congestion, delivery ratio degradation etc.).

Fig. 16(a) compares the results on alert delivery ratio for the three protocols obtained for the UCSD scenario. A relatively large size of the SE coupled with the increased alert traffic created due to the events result in a performance degradation somewhat similar for all three protocols. Meantime, Fig. 16(b) presents the drop in delivery ratio observed for the Helsinki scenario in comparison to the UCSD scenario under the same traffic conditions. Thus, a higher geographical dispersion of users in the Helsinki scenario results in a higher dispersion (within the network) of sensor alerts that are delivered to the users, and an increase of traffic load created by the

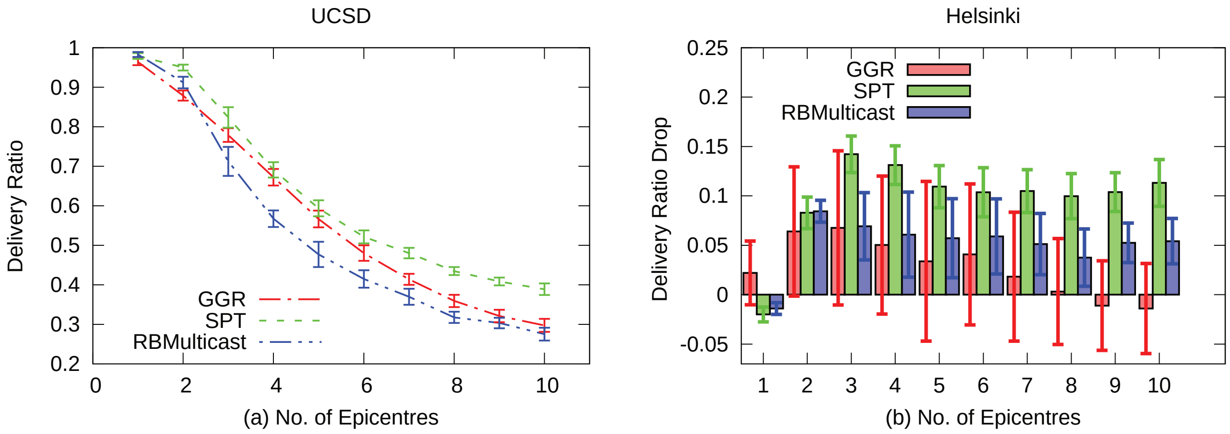


Fig. 16. Effect of user behavior: (a) Delivery ratio for the UCSD scenario; (b) drop in delivery ratio for the Helsinki scenario in comparison to the UCSD scenario.

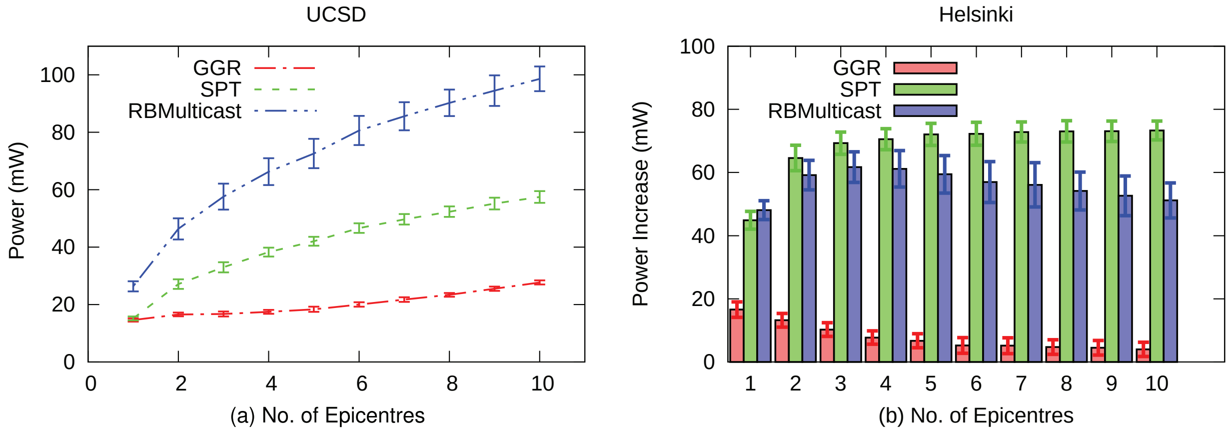


Fig. 17. Effect of user behavior: (a) Power consumption for the UCSD scenario; (b) network power consumption increase for the Helsinki scenario in comparison to the UCSD scenario.

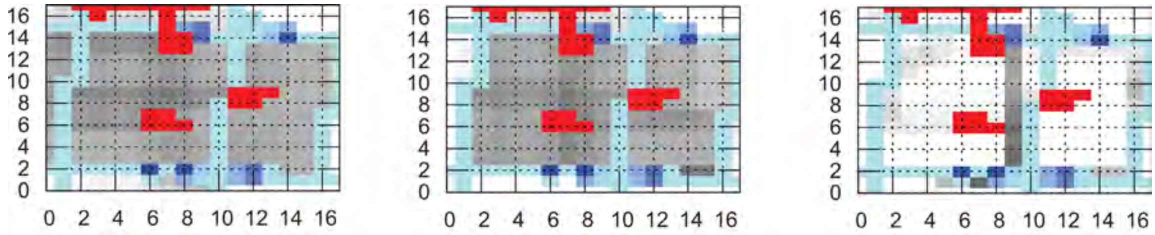
alert delivery. This increase is partially mitigated by GGR and RBMulticast protocols where alert propagation is performed via a set of clusters identified amongst those sensors. The SPT protocol does not incorporate such a clustering technique, which makes its performance the most vulnerable. Fig. 17 shows the same effect but for the aggregate power consumption of the environmental sensors.

Fig. 18 illustrates the differences in alert-delivery processes of the three protocols. The figure includes six heat-maps representing packet forwarding within the SE. The results are accumulated during 12:00–13:00 and 19:00–20:00 time intervals of one of the simulation runs for the Helsinki scenario. The heat-maps follow a particular color scheme representing the setup used for the simulation run. Thus, red is used to mark regions of sensor-alert origin within the environment. User presence for the considered time intervals is presented by color-grades ranging from light-blue to blue. Blue regions have higher user-densities that typically originate due to continuous users presence at specific locations (i.e. work places, restaurants, etc.). These regions could be also easily located on Fig. 15(b). Light-blue represent regions that users mainly pass through. Such a presence is typically low and may be less visible on Fig. 15(b). Finally, intensity of the packet forwarding by the environmental sensors is depicted by color-grades ranging from white to black, where darker color corresponds to higher intensity. The intensity is shown only for the sensors other than those associated with user presence and/or alert generation due to their natural involvement in the alert-delivery process.

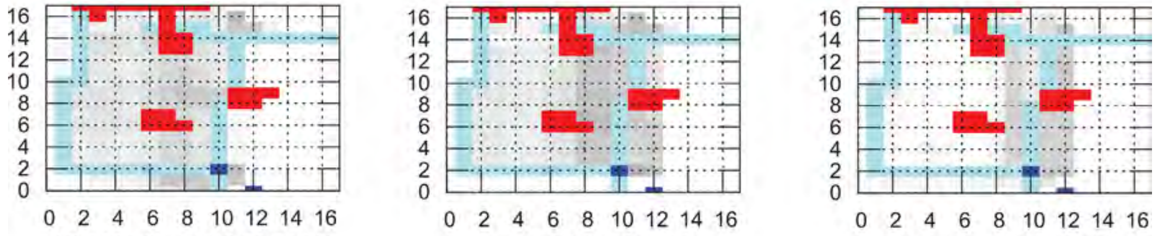
As it can be seen from Fig. 18(d)–(f), all three protocols limit the area-delivery process to the areas of expected user presence. Meanwhile, due to possible user presence along a border of a specific area (i.e. the area enclosed by the streets considered in the Helsinki scenario), the alert delivery of SPT and RBMulticast protocols also involves sensors within the area. Usage of these sensors is significantly reduced in case of the GGR protocol due to the use of the gravity-based concept. This illustrates how user behavior/group mobility may influence the alert delivery, and shows a certain degree of robustness of the proposed GGR solution.

6. Related work

Although wireless routing have received considerable attention from the research community, only a limited number of studies focus on either “many-to-many” or “any-to-many” communication protocols. While majority of the routing solutions for WSNs concentrate on conventional sensor-to-gateway communication, “many-to-many” and “any-to-many” communication patterns are more suitable for Fog Services, especially those of the type considered in the article. A truly Fog-oriented routing solution should represent a distributed routing protocol, that supports communication patterns of the Fog Services, while insuring efficiency of the information delivery. The solution will need to be highly dynamic to support potentially changing needs of the Fog Service (e.g., changing user-presence through out the day), be reactive to load heterogeneity, easily integrate with data fusion solutions tech-



(a) RBMulticast (12:00-13:00) (b) SPT (12:00-13:00) (c) GGR (12:00-13:00)



(d) RBMulticast (19:00-20:00) (e) SPT (19:00-20:00) (f) GGR (19:00-20:00)

Fig. 18. Effect of user mobility behavior on alert forwarding within the environment at different times of the day. The color schemes are as follows: The *alerts* are the *red* scales; the *user presence* are the *blue* scales, while the *packets forwarded* are the gray scales. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

niques. In this section we overview existing techniques that can support of the Fog Alert Services considered in this paper.

6.1. Topology-based routing

Topology-based solutions make use of various graph-theoretic node structures (trees, multi-trees etc.) found within the network. Thus, some of the solution (e.g., Lee et al. [14]) advocate usage of a network backbone, common for all of the network nodes. The backbone defines data delivery routes for unicast as well as multicast communication and therefore significantly simplifies information exchange within the network. However, various costs (e.g., bandwidth, energy) of the backbone construction and maintenance present a significant disadvantage. While some of the research target minimization of such costs (e.g., location-based node-clustering [15]), an alternative approach of on-demand routing is also presented in the literature. For example, for each multicast communication, Leung and Song [16] suggest building an independent Steiner tree that connects the sender and the receivers. The tree is built on-demand in a distributed fashion via a min–max tree-finding algorithm that simplifies complexity of the routing. Mottola and Picco [17] propose a solution that improves performance of the network by merging a number of multicast trees built for sources with the same recipients into a single multi-tree. Motskin et al. [18] present a mesh-network solution that provides users with information from a fixed set of sources. Each source is connected to its destinations through a specific hierarchical well-separated tree that is established within the network during run-time. Similar problem was considered by Tu et al. [19] who developed a solution for video multicasting from a set of gateways via a large wireless mesh network. Even though on-demand routing allows avoiding costs of the network back-bone maintenance, the approach has its own limitations. For instance, for the scenario considered in this article frequent alerts within the SE will result in frequent multicast routing and will, consequently, affect the efficiency of the overall SE. Furthermore, additional modifications will be required to accommodate data fusion in case of the on-demand routing. The modifications will need to ensure existence of common nodes amongst the delivery paths built for different alert source. Meanwhile, Gravity Concept of routing naturally accommodates data fusion.

6.2. Geographic routing

As an alternative to topology-based routing the approach of geographic multicasting, or geo-casting has been proposed in the literature. The approach presents a packet delivery process that relies on the geographical location of the network nodes rather than the network connectivity graph. The approach assumes that each node is aware of its own location (e.g., GPS coordinates), while each multicast sender is also aware of the locations of its receivers. For example, authors in [20,21] present techniques of restricted flooding that target specific geographical areas of location of the multicast receivers. Such flooding solutions are quite effective for scenarios where the destinations are expected to form relatively dense groups (e.g., multicasting data to a moving group of soldiers) within the environment. Meanwhile, their performances degrade when there is an increase in the sparsity of receivers' locations. Therefore, various research propose using location information to define multicast data-delivery routes within the network. For example, Galluccio et al. [22] propose a solution where each sender and receiver are required to build a multicast tree in a hop-by-hop fashion by minimizing the accumulative physical distance towards the receivers. [23], a hop-by-hop technique is proposed, where the multicast tree is established with respect to the directions from the location of the current hop towards the locations of the receivers. Feng et al. [11] present a quadrant-based hop-by-hop technique. Overall, in the case of geographic routing, node location presents a global information used by the network to simplify routing. However, potential discrepancy between geographic distance and network hop-count may affect optimality of the discovered routes. Also, similar to the on-demand routing (see previous subsection) geographic routing requires specific modifications to accommodate data fusion that is strongly beneficial for the considered application scenario. We compare our solution with the top state-of-the-art geographic routing solution, namely RBMulticast [11]. Performance of GGR protocol matches RBMulticast in terms of alert delivery ratio, while minimizing energy consumption of the network.

7. Conclusions

Engineering and design of Wireless Sensor devices and their network has significantly improved over the last number of years. The improvement has resulted in an increase of computational capacity of Wireless Sensor Networks. In view of that Fog Computing paradigm has been introduced by CISCO, where functionality of applications and services is proposed to be hosted by near-user devices or edge device such as wireless gateways and sensors. In this articles we have considered a possible Fog Implementation of WSN-based Alert Services. In particular, we have focused on targeted WSN-alert delivery based on direct interaction amongst user devices and sensors, as part of a Fog Service. We have proposed a solution that allows wireless sensors to be merged into a single Sensor Environment (SE) that delivers alerts generated by the sensors to the users. The alert delivery represents a user-aware multicast process lead by user presence within the SE. The multicast process uses our Gravity Routing Concept that has been carefully considered and proven for the case of wireless networks whose connectivity graphs are convex representable on compact. The multicast process is incorporated with an adaptive routing technique, namely the Gradient Routing. The resulting Gradient Gravity Routing (GGR) protocol presents the core of the proposed solution. The protocol has been evaluated through a series of simulations that compare its performance against two state-of-the-art techniques: RBMulticast and SPT. The simulation has considered performance of the three protocols for a large variety of alert scenarios and has shown higher efficiency of GGR protocol due to its effective use of data fusion. The simulation work has also evaluated the ability of GGR to adapt to various traffic heterogeneities within the SE. The evaluation shows that the adaptation improves the quality of the alert delivery of the SE, however, the improvement comes at a certain energy-related price. Performance gain from using the proposed solution is also influenced by the end-user behavior/group mobility, where an example of such an influence has been provided in the article. Our evaluation shows that alert delivery of GGR protocol has a higher degree of robustness to fluctuations of user behavior.

By integrating a certain level of intelligence driven by dynamic user group mobility into the Wireless Sensor Networks, our proposed GGR routing has shown how a Fog Alert Service can be developed. The proposed approach will minimize the frequency interactions between the Wireless Sensor Networks and the cloud, while enabling services to be developed in the Fog to allow spontaneous information delivery as the user moves through the network.

Acknowledgments

This work has received support from the Science Foundation Ireland (SFI) and the Agriculture and Food Development Authority, Ireland (TEAGASC) as part of the SFI TEAGASC Future Agri-Food Partnership, in a project (13/IA/1977) titled “Using precision technologies, technology platforms and computational biology to increase the economic and environmental sustainability of pasture based production systems”. This work was also supported by the Finnish Academy Research Fellow program under Project no. 284531, and the Science Foundation Ireland (SFI) via the CONNECT research centre under Grant 13/RC/2077.

References

[1] F. Bonomi, R. Milito, J. Zhu, S. Addepalli, Fog computing and its role in the internet of things, in: Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing (SIGCOMM) (MCC’12), ACM, New York, NY, USA, 2012, pp. 13–16, doi:10.1145/2342509.2342513.

[2] H. Abu-Ghazaleh, A. Alfa, Application of mobility prediction in wireless networks using Markov renewal theory, IEEE Trans. Vehic. Technol. 59 (2) (2010) 788–802.

[3] S. Scellato, M. Musolesi, C. Mascolo, V. Latora, A. Campbell, Nextplace: A spatio-temporal prediction framework for pervasive systems, in: The 9th International Conference on Pervasive computing (Pervasive), Springer Berlin Heidelberg, 2011, pp. 152–169.

[4] Y. Chon, E. Talipov, H. Shin, H. Cha, Mobility prediction-based smartphone energy optimization for everyday location monitoring, in: The 9th ACM Conference on Embedded Networked Sensor Systems (SenSys’11), ACM, 2011, pp. 82–95.

[5] E. Gaura, J. Brusey, M. Allen, R. Wilkins, D. Goldsmith, R. Rednic, Edge mining the internet of things, IEEE Sens. J. 13 (10) (2013) 3816–3825.

[6] S. Ivanov, D. Botvich, S. Balasubramaniam, N. Popova, Avoiding redundant channel blocking in cooperative multi-channel mac protocols through virtual topology inferencing, in: the 2nd IEEE Cooperative Mobile Networks (CoCoNet2), Collocated with IEEE ICC, IEEE, 2009, pp. 1–5.

[7] D. Bertsekas, Convex Optimization Theory, Athena Scientific, Belmont, MA, 2009.

[8] Y. Gu, Y. Tian, E. Ekici, Real-time multimedia processing in video sensor networks, Signal Proces.: Image Commun. J. (Elsevier) 50 (17) (2006) 3449–3465.

[9] Y. Tian, E. Ekici, Cross-layer collaborative in-network processing in multihop wireless sensor networks, IEEE Trans. Mobile Comput. 6 (3) (2007) 297–310.

[10] M. McNett, G. Voelker, Access and mobility of wireless pda users, Mobile Comput. Commun. Rev. 9 (2) (2005) 40–55.

[11] C.-H. Feng, Y. Zhang, Stateless Multicast Protocol for Ad Hoc Networks, IEEE Transactions on Mobile Computing 11 (2) (2012) 240–253.

[12] H. Takahashi, A. Matsuyama, An approximate solution for the steiner problem in graphs, Math. Japon. 24 (1980) 573–577.

[13] A. Keranen, J. Ott, T. Karkkainen, The one simulator for dtn protocol evaluation, in: The 2nd International Conference on Simulation Tools and Techniques (Simutools’09), ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2009, pp. 1–10.

[14] M. Lee, R. Zhang, J. Zheng, G. Ahn, C. Zhu, T. Park, S. Cho, Ieee 802.15.5 wpan mesh standard-low rate part: Meshing the wireless sensor networks, IEEE J. Select. Areas Commun. 28 (7) (2010) 973–983.

[15] X. Xiang, X. Wang, Y. Yang, Supporting efficient and scalable multicasting over mobile ad hoc networks, IEEE Trans. Mobile Comput. 10 (5) (2011) 544–559.

[16] V. Leung, G. Song, A distributed algorithm for min-max tree and max-min cut problems in communication networks, IEEE/ACM Trans. Netw. 18 (4) (2010) 1067–1076.

[17] L. Mottola, G. Picco, Muster : Adaptive energy-aware multisink routing in wireless sensor networks, IEEE Trans. Mobile Comput. 10 (12) (2011) 1694–1709.

[18] A. Motskin, I. Downes, B. Kusy, Gnawali, L. Guibas, Network warehouses: Efficient information distribution to mobile users, in: The 30th IEEE International Conference on Computer Communications (IEEE INFOCOM’11), IEEE, 2011, pp. 2069–2077.

[19] W. Tu, C. Sreenan, C. Chou, A. Misra, S. Jha, Resource-aware video multicasting via access gateways in wireless mesh networks, IEEE Trans. Mobile Comput. 11 (6) (2012) 881–895.

[20] G. Zhao, X. Liu, A. Kumar, Geographic multicast with K-means clustering for wireless sensor networks, in: IEEE Vehicular Technology Conference (VTC), IEEE, 2008, pp. 233–237.

[21] H.-S. Mo, S. Park, J. Lee, H. Park, S.-H. Kim, Energy efficient data dissemination protocol for a mobile sink group in WSNs, in: The 22nd IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, IEEE, 2011, pp. 2269–2273.

[22] L. Galluccio, G. Morabito, S. Palazzo, GEographic multicast (GEM) for dense wireless networks: Protocol design and performance analysis, IEEE/ACM Trans. Netw. 21 (4) (2013) 1332–1346.

[23] E. Lee, S. Park, J. Lee, S.-H. Kim, Geographic multicast protocol for mobile sinks in wireless sensor networks, IEEE Commun. Lett. 15 (12) (2011) 1320–1322.

Stepan Ivanov received the Diploma (with honours) in applied mathematics and informatics from the Moscow State University, Russia. Directly after completing his Diploma, he joined the Telecommunications Software & Systems Group (TSSG) in Waterford Institute of Technology, where he worked towards the Ph.D. degree. He has recently been awarded a Ph.D. in computer science, and is currently working in the TSSG as a post-doctoral researcher. Since joining, he has been involved in a number of research project. He has more than 5 years of research experience and is the lead author of several peer-reviewed conference and journal papers on the topic of bio-inspired network management, wireless sensor networking and performance modelling.

Sasitharan Balasubramaniam (SM'14) received the bachelor (electrical and electronic engineering) and Ph.D. degrees from the University of Queens- land in 1998 and 2005, respectively, and the masters' (computer and communication engineering) degree in 1999 from the Queensland University of Technology. He is currently an Academy of Finland Research Fellow at the Nano Communication Centre, Department of Electronic and Communication Engineering, Tampere University of Technology, Finland. He has published more than 70 papers and actively participates in a number of technical programme committee for various conferences. He is the General co-chair for ACM NANOCOM 2015 and was the TPC co-chair for ACM NANOCOM 2014 and IEEE MoNaCom 2011, both conferences which he co-founded. He is currently an editor for the IEEE Internet of Things journal and Elsevier Nano Communication Networks. His current research interests includes bio-inspired communication networks, as well as molecular communications. He is an IEEE Senior member.

Dmitri Botvich (M'05) received the bachelor and Ph.D. degrees in mathematics from Lomonosov Moscow State University, Faculty of Mechanics and Mathematics, Russia, in 1980 and 1984, respectively. He is currently a Senior Researcher at LIGM Lab of University Paris-Est, Marne-la-Vallee (France). He has worked in a number of Irish funded projects (e.g. Science Foundation Ireland, PRTLI) and EU projects. He has published more than 150 papers in conferences and journals. His research interests include wireless networking, network management, bio-inspired techniques, privacy, security, trust management, queuing theory and optimization methods.

Ozgur B. Akan (M'00, SM'07) received the Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, in 2004. He is currently a full professor with the Department of Electrical and Electronics Engineering, Koc University and the director of the Next-Generation and Wireless Communications Laboratory. His current research interests include wireless communications, nanoscale and molecular communications, and information theory. He is currently the General Co-chair of ACM Mobicom 2012, IEEE MoNaCom 2012, and the TPC Cochair of IEEE ISCC 2012. He is an associate editor of the IEEE Transaction on Vehicular Technology and IEEE Transactions on Communications, International Journal of Communication Systems, and Nano Communication Networks Journal.