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Environmental monitoring aware routing: making environmental sensor networks more robust

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Abstract Wireless Sensor Networks (WSNs) have a broad application range in the area of monitoring and surveillance tasks. Among these tasks, disaster detection or prevention in environmental scenarios is one typical application for WSN. Disasters may for example be forest fires, volcano outbreaks or flood disasters. Here, the monitored events have the potential to destroy the sensor devices themselves. This has implications for the network lifetime, performance and robustness. While a fairly large body of work addressing routing in WSNs exists, little attention has been paid to the aspect of node failures caused by the sensed phenomena themselves. This paper presents a proactive routing method that is aware of the node's destruction threat and adapts the routes accordingly, before node failure results in broken routes, delay and power consuming route re-discovery. The performance of the presented routing scheme is evaluated and compared to OLSR based routing in the same scenario.

Keywords Environmental awareness · WSN routing

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1 Introduction

The majority of wireless sensor network applications are designed to monitor events or phenomena, that is the temperature in a room, the humidity in a particular space, the level of contaminants in a lake, soil moisture in a field, etc. A specific monitoring application for wireless sensor networks is monitoring of areas which are of risk of geological, environmental or other disasters. Examples are natural events such as floods, volcano outbreaks, forest fires, avalanches, and industrial accidents such as the wide spread leakage of harmful chemicals.

A common aspect of all these disasters is that they bear the potential to destroy the very sensor nodes that are monitoring the area to detect the desaster events. This means that sensor nodes are not available for routing of data anymore shortly after they have detected the event, e.g. they have burned in a forest fire for example, and therefore routes have to be changed or re-discovered to adapt to these changed conditions in order to continue the monitoring task of the network. This requires an effective mechanism that can make sure that the sensor network remains operational as long as possible in order to fulfil its monitoring task.

However, most existing routing protocols consider the lifetime of a sensor node as only dependent on the energy resources of that node, i.e. a node is assumed to fail only when the battery is depleted. Well known routing protocols such as LEACH [1], PEGASIS [6], TEEN [7], Directed Diffusion [2], SPIN [4], Maximum Lifetime Energy Routing [3], and Maximum Lifetime Data Gathering [12], all focus on energy as the primary objective to making routing decisions. While energy conservation is critical for wireless sensor networks that are deployed in the environment, it is not necessarily the best approach in particular when sensing hazardous phenomena that threaten the operation of the network when it matters most.

Here we present Environmental Monitoring Aware (EMA) routing, a routing method that is "context-aware" in the sense that it adapts its routing tables based on the imminent failure threat due to the sensed phenomenon. While EMA also attempts to be power efficient, it proactively avoids route breaks caused by the disaster-induced node failures and thus increases network reliability and availability when it matters most from the application's perspective. In order to evaluate our proposed EMA routing approach, we have simulated a forest fire scenario within an OPNET simulation model. Simulation results show that the proposed approach results in a more resilient network and lower end-to-end delays compared to other well known protocols.

The remainder of the paper is structured as follows; related work is presented in Sect. 2, the proposed routing algorithm is described in Sect. 3. Section 4 introduces the disaster scenario, which we have chosen to evaluate the routing algorithm. The simulation setup and evaluation results for a single sink scenario are shown and discussed in Sect. 5. Following, we also show, in Sect. 6, how EMA can operate effectively with multiple redundant sinks. The paper ends with conclusions and outlook in Sect. 7.

2 Related work

Wireless sensor network routing protocols that consider the application "context", include the Sensor Context-Aware Routing protocol (SCAR) [8], which utilizes movement and resource predictions for the selection of data forwarding directions. The protocol is an adaptation of the Context-Aware Routing protocol (CAR) [9] to wireless sensor networks. In SCAR, each node evaluates its connectivity, co-location with sinks and remaining energy resources. Based on the history of these parameters, a forecast is made and the forecasted values are combined into a delivery probability for data delivery to a sink. Information about this delivery probability and the available buffer space is periodically exchanged with the neighbor nodes. Each node keeps an ordered list of neighbors sorted by the delivery probability. When data is to be sent, it is multicast to the first R nodes in the list (R being a user-specified value), thus exploiting multiple paths to increase the reliability of delivery.

Energy and Mobility-aware Geographical Multipath Routing (EM-GMR) [5] is a routing scheme for wireless sensor networks that combines three context attributes: relative distance to a sink, remaining battery capacity and mobility of a node. The mobility is only used in a scalar form indicating the speed, but not the direction of movement. Each of the three context attributes is mapped to three fuzzy levels (low, moderate, high), leading to a total of $3^3 = 27$ fuzzy logic rules. The result of these rules—the probability that the node will be elected as forwarding node—is a fuzzy set with 5 levels: Very weak, weak, moderate, strong, very strong. Each node maintains a neighbor list which contains all N neighbors and is sorted by these 5 levels, and it chooses the topmost M ($M < N$) nodes as possible forwarding nodes from the list. Then it sends a route notification (RN) to these nodes requesting whether they are available. Upon receipt of a positive reply, the data is sent.

The protocols discussed above utilize context attributes such as relative position, remaining energy, mobility or connectivity to make routing decisions. While the algorithm proposed in this paper also uses different context attributes, it extends the literature in that it uses measurements of an external influence, the very phenomenon that the nodes sense, to adapt routes to avoid external threats.

3 Environmental monitoring aware routing

The intention of the work reported here is to create a routing method that can adapt to external node threats, the very threats that are being sensed/monitored. The node's health, affected by the sensed phenomenon, is the most relevant routing criterion here. Additionally, there have to be criteria, e.g. link quality, that allow efficient routing when all nodes are equally healthy. These are parameters that indicate the connectivity and the direction to the destination.

Based on these requirements, the parameters used as routing criteria in the proposed EMA approach are the health status, the RSSI (Received Signal Strength Indicator) and the hop count of the respective route.

The health status is defined to be a value between 0 and 100, with 0 being the worst and 100 the best health. If the node's temperature is below a lower threshold, the health status is 100, if it is (or has been) above an upper threshold, the health status is 0, indicating that the node is likely to fail at any time. Between the two thresholds, the health is linearly dependent on the temperature. This is clearly a simplified approach. However, the main focus of this work is not elaborate modelling of the nodes' health with respect to temperature but rather the study of routing mechanisms that avoid unhealthy nodes.

3.1 Route update signaling

The sink initiates route updates in the network by sending out a beacon. This *sink beacon* contains information about the sink's health and a hop count of 0. A sensor node which receives a sink beacon determines the RSSI and updates an internal *sink table* with the new information, including the measured RSSI value. It then increases the hop count by 1 and compares its own health to the health value in the received beacon. The lower of these two health values is included in the beacon message so that it contains the lowest health value on the route. Additionally, the RSSI value is added to the beacon so that a quality indication of the path is available for the next nodes. After these changes, the beacon is rebroadcast.

The rebroadcast beacons (*neighbor beacons*) are then received by nodes that are not in direct communication range of the sink. Upon receipt of a neighbor beacon, the node compares the current information about health, RSSI and hop count to the information it might already have about the sending neighbor node and updates its internal *neighbor table* accordingly. Then it elects its best neighbor node. If there is a change related to the best neighbor, the beacon is rebroadcast with updated health, RSSI and hop count information. A "change related to the best neighbor" means that one of the following conditions is fulfilled:

- a new best neighbor is elected,
- a new beacon was received from the current best neighbor.

If there is no change related to the elected best neighbor, the neighbor beacon is not rebroadcast to save energy and to reduce network load. As new beacons from the current best neighbor are always forwarded, new sensor nodes that are joining the network can easily be integrated as beacons occur regularly. To avoid that the death of a best neighbor remains undiscovered, a timeout is defined after which a neighbor table entry becomes invalid. In the case of a timeout, a new best neighbor is elected.

3.2 Best neighbor election

The node sorts both its neighbor table and its sink table according to a weighted multiplicative metric. The general form of this metric is

$$M = \prod_{i=1}^{N} (f_{s,i}(p_i)) \tag{1}$$

where p_i is parameter i and $f_{s,i}$ is a shaping function that maps p_i to the interval $[0, 1]$. In the case of the neighbor table, the parameters are the health, the hop count and the RSSI. The choice of the node health is obvious because it represents the environmental influence that we want to utilise in the new routing approach. The hop count is chosen as it favors short routes and thereby reduces energy consumption. The RSSI as a third parameter represents the signal quality on a route and helps chosing routes with low probability of transmission errors and packet losses. For the chosen parameters, the following settings were applied:

- *The health* is a parameter defined between 0 and 100. As good health is preferable, a linear downscaling, dividing by 100, can be used for this criterion.
- *The hop count* can be any non-negative integer value. As low hop counts are preferable, the shaping function should have its maximum for a hop count of 0 and be 0 for an infinite hop count. A negative exponential shaping function was chosen here because it facilitates mapping of the possible hop count range $[0\ \infty]$ onto the interval $[0\ 1]$, with 0 hops being mapped onto 1.
- *The RSSI value* is given in dBW, and as long as the transmission power of the nodes is below 1 W (which is usually the case in wireless sensor networks), the RSSI always has a negative value. A high RSSI is preferable here. The shaping function chosen here is a positive exponential function, which projects the value range $[-\infty\ 0]$ into the interval $[0\ 1]$. The exponent here has to be adapted to the usual value range of the RSSI in order to avoid that the RSSI criterion dominates the other two criteria.

The complete metric used here is

$$M = \frac{health}{100} * e^{-hopcount} * e^{\frac{RSSI}{50}}. \tag{2}$$

For sorting of the sink table, the metric does not use the hop count, as it is always the same for a direct link to a sink. The health and RSSI are used in the same manner as for the neighbor table.

The best neighbor selection then works as follows:

- *If sinks are in communication range*, the best sink is elected as best neighbor node, thus using direct communication to the sink whenever this is possible.
- *If no sink is in communication range*, a neighbor node has to act as a multi-hop relay towards the sink. In this case, the best node from the neighbor table is elected.

3.3 Sensor data transmission

Whenever a sensor node has data to send, communication to the sink takes place on a hop-by-hop basis. The sending node looks up the current best neighbor node in the neighbor table and forwards its data to that node. The receiving node then does the same, and in this way the data packets travel through the network until they reach the destination. Acknowledgments are also transmitted according to this hop-by-hop forwarding: there are no end-to-end acknowledgments, but instead there are acknowledgments on each hop. This is sufficient for most sensor network scenarios where end-to-end acknowledged transmissions are not required. If an application relies on end-to-end acknowledgements, e.g. to fulfill QoS requirements, there has to be an additional end-to-end acknowledgement support, which could be provided by only acknowledging a transmission if the subsequent hop has been acknowledged. In this case, however, acknowledgment timeouts have to be dimensioned according to the expected maximum hop count in the sensor network. In the forest fire scenario, end-to-end acknowledgements do not increase reliability.

4 Scenario description

The proposed routing scheme is studied within a forest fire scenario. A wireless sensor network is deployed in a forest area, with initially only one base station connected to a wireless wide area network and receiving all sensor measurements. All other nodes are identical in that they each have the same sensing, computation and communication capabilities. Temperature sensing is among these capabilities.

Within the simulated area, a fire breaks out and spreads across the simulated area. When the fire reaches a sensor node, its temperature will rapidly increase and quickly lead to a terminal node failure.

Figure 1 depicts the scenario we have studied here. The simulated area has a size of 10 km × 10 km. The node in the lower right corner which is labeled "sink_0" is the base station, the other 20 nodes are the deployed sensor nodes. As can be seen, the fire breaks out at the center of the area.

In the simulation, we consider that the forest fire breaks out 20 minutes after the simulation is started, which means the first 20 minutes of the simulation, the network is static, i.e. all nodes are stationary, and no nodes fail. By choosing this 20 minute period, potential transient effects of initial network setup can be safely discarded. To avoid an unrealistic, circular spread of the fire, but still keeping the scenario simple, an elliptical spread is assumed with a spreading speed of 1 m/s on the minor axis and 2 m/s on major axis of the ellipse. Actually, this spread is faster than a typical forest fire spread leading to a worst case spread which requires maximum reactivity in the network. The ellipse's angle (in radians) with respect to the coordinate system is 0.5. The elliptical shape visualizes the ellipse's angle and the ratio between the major and minor axes. When the expanding fire ellipse reaches a node, its temperature increases rapidly. The maximum temperature a node can withstand is set to 130 degrees Celsius, when the value is above this threshold, the node dies (which means it is completely deactivated in the simulation).

The nodes measure the temperature every 15 seconds and transmit the obtained values to the base station as input into a forest fire detection algorithm and fire fighter alerting. We have modelled an individual starting time for a nodes' first measurement to avoid effects caused by synchronous transmissions of all nodes. As the temperature might not be the only data that a node is sending, the measured values are part of a data packet of 1 kBit size. This means each node transmits 1 kBit every 15 seconds, resulting in an overall net data rate requirement of 1.33 kBit/s or 1.33 packets/s.

The transmission power, which is equal for all nodes in the scenario, is chosen to 1 mW (−30 dBW), and the receiver sensitivity is assumed to be unlimited. A receiver sensitivity limit would simply mean downscaling scenario dimensions if the assumed noise floor is raised accordingly. The use of the settings for transmitters and receivers implies that multiple hops are required to reach the sink. Only the four nodes that are closest to the sink are in direct communication range with it.

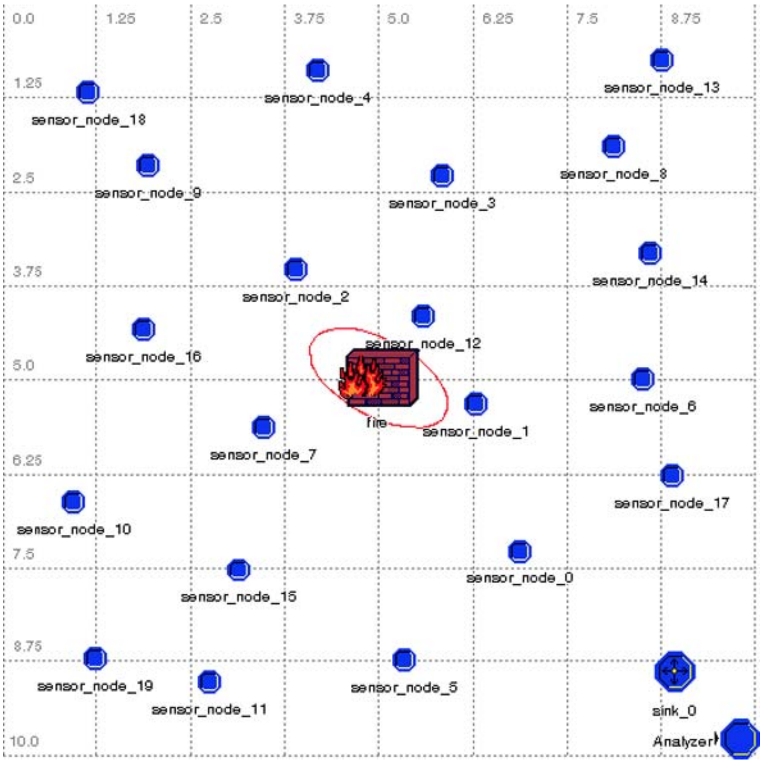

Fig. 1 Scenario layout

5 EMA in a single-sink scenario

The simulations for the evaluation of the proposed routing method were performed using the network simulator OPNET [11] with the simulation layout described in the previous section of this paper. The MAC (Medium Access Control) and PHY (Physical) layers in the node model are based on the Open-ZB [10] implementation (version 1.0) of the 802.15.4 stack. Different from the original Open-ZB model, the MAC layer was modified to support an ad-hoc mode with unslotted CSMA/CA instead of the original PAN-coordinated mode. This modified MAC layer was first used in work reported in [13].

We simulated the scenario for a model time of 90 minutes. Several statistics were collected and are shown in the following. OLSR (Optimized Link State Routing) was chosen as a protocol for comparison. The existing OLSR implementation of OPNET's wireless module was used and the PHY and MAC layers were replaced with the 802.15.4 layers. OLSR is a standard proactive routing protocol for ad-hoc networks and can therefore be considered as the base line protocol for proactive routing studies. To achieve comparability, the route lifetime is set to 30 seconds in both, EMA and OLSR simulation scenarios. EMA beacons are transmitted at intervals of 15 seconds, OLSR hello messages at the same intervals. OLSR topology control (TC) messages are transmitted at 30 second intervals.

The applied temperature model is simple: As long as a node is not exposed to fire, its temperature values are normally distributed with a mean of 20 degrees Celsius and a standard deviation of one degree Celsius. When the node becomes exposed to the fire, a linearly growing offset is added to the node's temperature value. Figure 2 shows the temperature curve at sensor node 1, a node that is located close to the fire breakout location. It can be seen that in the applied temperature model, the temperature increases quickly when the fire reaches the node, which in the illustrated case happens at ca. 1900 seconds of model time. Within a short time, the maximum temperature threshold is reached and the node dies.

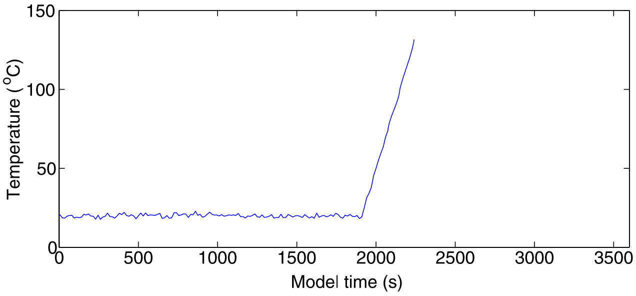

Fig. 2 Temperature graph according to the applied temperature model, at the example of sensor node 1

This temperature graph is shown to illustrate the conditions the nodes experience when the fire reaches them. Real temperature curves might have a smoother nature, which would make it even easier for a health-aware routing protocol to adapt to the changing conditions.

Figure 3 shows the packet reception statistics from the individual sources (sensor nodes) at the sink. The values on the ordinate are the IDs of the sensor nodes. Each cross marks the reception of an individual packet from the respective source at the sink. A continuous incoming flow of data from each node is visible (although the interarrival times vary in some cases). The flow of data stops abruptly when the node dies.

The EMA algorithm performs as intended as data from all sensor nodes reaches the sink, and inflow of data packets continues until sensor nodes die. As Fig. 3 does not directly show how much of the generated traffic is received at the sink, the incoming packet rate is compared to the generation rate in Fig. 4.

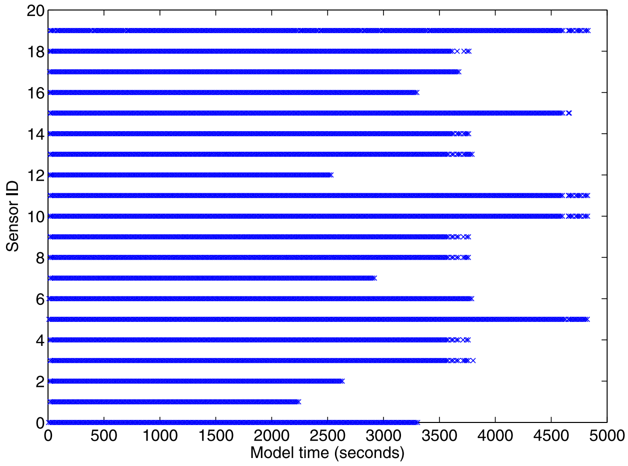

Fig. 3 Incoming packet flows at the sink

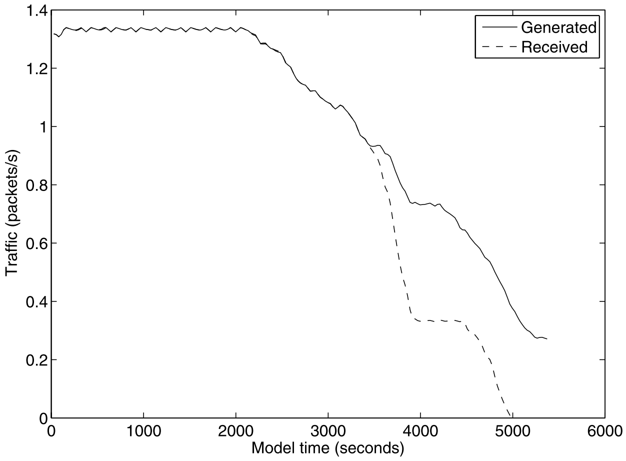

Fig. 4 Traffic generated and received at the sink in packets/s (EMA routing)

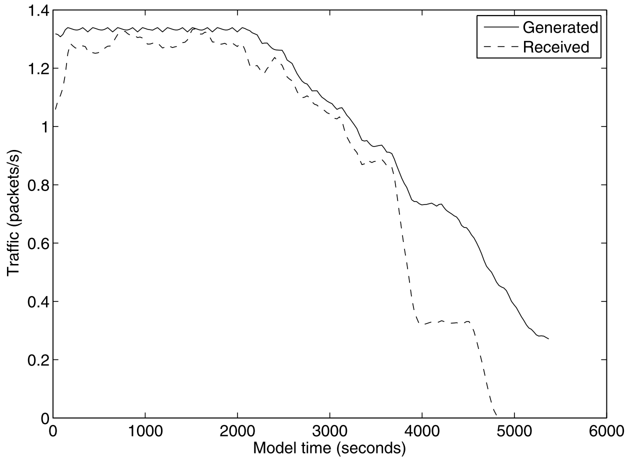

Fig. 5 Traffic generated and received at the sink in packets/s (OLSR routing)

The death of nodes leads to less data traffic being generated and being received at the sink. This can be seen in the packet generation and reception rates shown in Fig. 4. The solid curve shows the generation rate, the dashed curve shows the reception rate. Both curves show moving average values in a 250 s time window, so that the curves are smoother and the difference between generation and reception is more visible. For comparison, the packet generation and reception rates were also measured in the OLSR simulation and are shown in Fig. 5.

From Fig. 4, it can be seen that until around 3500 seconds of model time, the incoming packet rate is on the level of the generated rate, which is 1.33 packets/s when all nodes are alive (see Sect. 4). The steep drop that follows is caused by the failure of sensor node 17. When this node fails, the nodes in the upper right area can not reach the sink any more. The second significant drop is the failure of sensor node 5, after which no node can reach the sink any more (sensor node 0, which is also close to the sink, has already failed before). Figure 3 shows quite clearly that there are several nodes from which no more data is received when node 17 fails, and similarly for the failure of sensor node 5. These results show that the protocol succeeds in changing the routing in time before transmission problems occur, so that the nodes are able to deliver their data as long as there is a way to reach the sink. The OLSR results shown in Fig. 5 show a lower and varying incoming packet rate throughout the simulation. This means there are less successful transmissions in the OLSR scenario. Similar observations were made for AODV (see [14]). The reason for these problems even in the case of a static network is that neither AODV nor OLSR use context values such as the RSSI values. This leads to potential elections of routes with low RSSI, which in turn causes transmission failures.

Another performance measure that was recorded in the simulations were the end-to-end delays. These were not recorded for each source node separately, but across all source nodes. Figure 6 shows a histogram of the end-to-end delays for both routing methods.

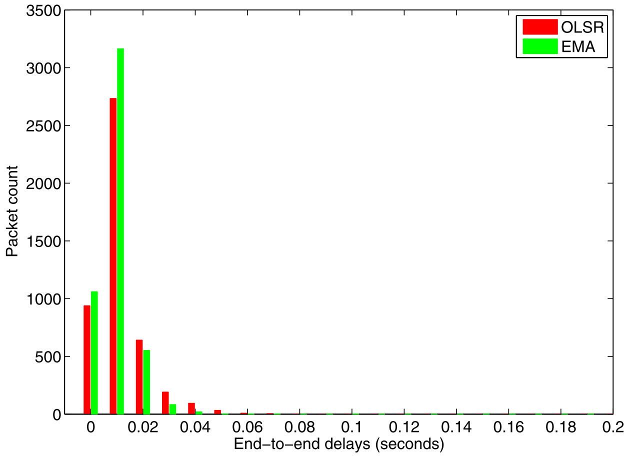

Fig. 6 End-to-end delay histogram for EMA and OLSR

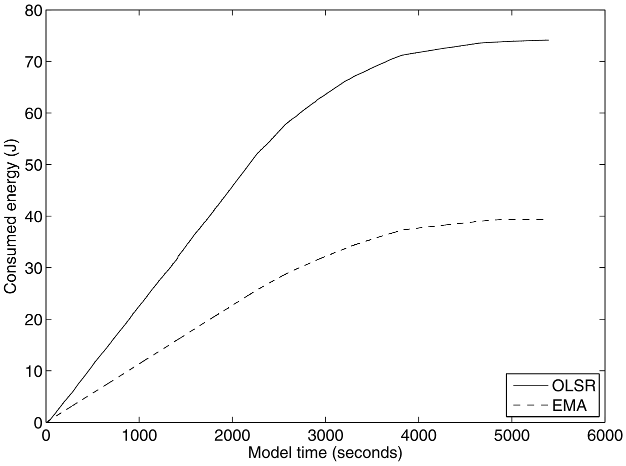

Fig. 7 Network-wide energy consumption

The histogram depicted in Fig. 6 shows that generally, the delays are quite similar for both algorithms, with a minor advantage on the side of the proposed EMA algorithm. However, in comparison to the measurement intervals of 15 seconds, the delays are negligible for both algorithms.

The third recorded performance measure is energy consumption. The comparison of the consumption for EMA and OLSR is shown in Fig. 7. The graphs here show the overall energy consumed in the network since the start of the simulation.

A significant difference can be seen in these energy consumption graphs. EMA consumes much less energy, approximately half of what is consumed by OLSR. This is caused by the differences in how the route tables are proactively maintained: While EMA uses beacon forwarding and only forwards beacons that are relevant, OLSR uses two types of regularly transmitted messages: hello messages and TC messages. While hello messages are broadcasted, but not forwarded, TC messages are flooded into the network, causing a significant signaling overhead.

The comparisons show clearly that the proposed EMA routing approach is superior to the OLSR routing protocol in the given scenario.

6 EMA with multiple sinks

To ensure a higher probability of successful data delivery, it can be advantageous to add multiple redundant sinks to the network. Redundant here means that all sinks have exactly the same functionality, so that any of them can act as receiver for the sensor data.

In OLSR, this is problematic as the sensor nodes need to specify a destination address when they transmit their data. This means the sinks either have to have the same address, or the nodes have to multicast their data. Having multiple nodes with the same address causes further protocol problems, as OLSR is not designed to handle this. Multicasting, on the other hand, increases the overall traffic significantly as in this case sensor nodes need to perform multiple transmissions.

In contrast to the problems that occur with multiple sinks in an OLSR network, EMA does not have these problems, as the sensor nodes just elect their best neighbor and do not have to care about to which sink the transmission is directed. If there are multiple sinks, all of the sinks send out their beacons. The sensor nodes may then receive beacons from multiple sinks and just elect the best one as their best neighbor.

To verify this, the scenario depicted in Fig. 1 is modified by adding a second sink in the upper right corner and a third sink in the lower left corner. Adding the sinks to the corners is a reasonable placement in the given scenario, as the corners of the forest area are probably the physically most accessible locations.

Figure 8 shows the generated and delivered traffic in case of 1, 2 and 3 sinks. It can be seen that by placing the second sink in the upper right corner, the failure of sensor node 17 does not have the impact any more that it had in the single-sink case. Similarly, the impact of the sensor node 5 failure gets eliminated by the third sink in the lower left corner. When there are sinks in 3 corners of the simulation area, all sensor nodes can deliver their data throughout the complete simulation.

The energy consumption throughout the network is shown in Fig. 9. Interestingly, the consumption in the cases of 1 and 2 sinks is virtually identical. The reason is that shorter routes in the second sink's vicinity compensate for the additional energy that is spent for the second sink's beacons and their forwarding.

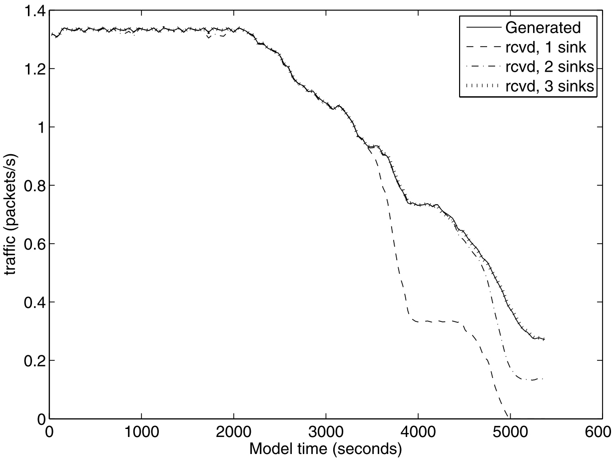

Fig. 8 Traffic generated and received at the sink (EMA routing with multiple sinks)

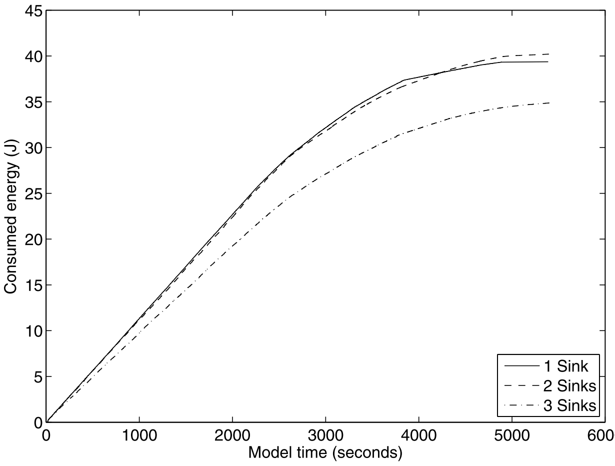

Fig. 9 Network-wide energy consumption with multiple sinks

In the case of 3 sinks, the overall consumed energy is less than in the other two cases, although the addition of each sink means one additional beacon transmitter. Here, the nodes that are located near the third sink have now also shorter routes towards a sink. This overcompensates for the additional beacon overhead.

7 Conclusion and outlook

We have proposed a routing approach that proactively adapts routes in a wireless sensor network based on information on node-threatening environment influences. The approach, called Environmental Monitoring Aware (EMA) routing, has been evaluated by computer simulation and has demonstrated good performance in the considered forest fire scenario. With respect to the considered network and performance parameters, it outperforms the proactive OLSR routing algorithm. In particular, EMA routing can support multiple sinks with no additional overhead. The routing approach is also more flexible than standard protocols in that additional environmental parameters can be added simply to the routing algorithm to adapt the approach to a wide range of applications.

Further research will include evaluation in further scenarios. A reactive variant of EMA will be investigated as well, and EMA will also be investigated in scenarios with sensor node mobility.

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