A Combined Routing Layer for Wireless Sensor Networks and Mobile Ad-Hoc Networks

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Abstract

In the near future, first responders such as firefighters might be supported by sensor nodes, both installed before the incident and placed by the responders themselves. To communicate with these sensor nodes, the first responders could be equipped with hand held devices, e.g. PDAs with wireless LAN, additionally equipped with a radio module of the same type as used by the sensor nodes. This scenario enables the usage of the PDAs as mobile communication backbone by the sensor nodes, as well as allowing the first responders to access nodes in the sensor network in an efficient way, both near and far. This paper presents a weighted routing protocol for heterogeneous networks, which could be used in such a scenario.

1 Introduction

In emergency scenarios such as fires or earthquakes, quickly deployed sensor networks can lend vital support to first responders like firefighters and rescue teams. When first responders arrive at the scene, they should be able to communicate with all sensor nodes in their immediate vicinity, or even nodes farther away, depending on the intended use. An application for the former would be firefighters, who measure the heat levels in the immediate area they are moving to, using sensors that have been installed in the building previously. An application for the latter would be finding the way out of the burning building for the same firefighters. If they dropped a few sensors on the way in, they could determine a safe route back. When they reach the trapped people, they would request the heat levels measured by the nodes at the entrances/exits of the building. If the values returned from some sensors are too high, or there is no answer at all, they would know that this route was not safe anymore and choose a different way out. Figure 1 shows an example of such a communication. The firefighters have entered the building from 3 different entrances and planted sensor nodes on the way. Now they meet in the center, and try do determine a safe route back out. Three of them request temperature values from the nodes they placed at the entrances. For simplicity the following communication back to the firefighters is not shown here.

Another application would be the communication among the firefighters. Currently this communication and the communication between a firefighter and the operation controllers is very lossy. If things go bad, and a house is about to collapse, the controllers send an evacuation signal. But sometimes, this signal is not received by all of the firefighters, leading to danger of injuries and sometimes even death.

In our approach the evacuation order would be sent over multiple networks - the currently used one, the wireless LAN of the PDAs and the sensor network. The specialty is, that the communication can switch between networks at any time. If specified, a message of high priority like an evacuation order received by a PDA will be flooded into the sensor network as well as the wireless LAN. This way, even firefighters who are not in direct communication range with any other can be reached through multiple sensor network hops. As this of course drains energy from the sensor nodes, a multiple network flooding should only be used in extreme cases, when it is absolutely vital to reach all firefighters. But the situation mentioned before is of course such one, as the life of the firefighters might be at stake. Figure 2 shows an example for such a communication. The PDA in the left upper corner just received an abort mission signal, which is then flooded through both networks. All PDAs within range receive it, and the corresponding firefighters evacuate. The firefighters carrying the PDAs in the right corner would normally not have received the signal, but are now evacuating, too, as the signal was relayed by the sensor nodes.

This paper is structured as follows: The weighted routing protocol is described in section 2, while section 3 shows the

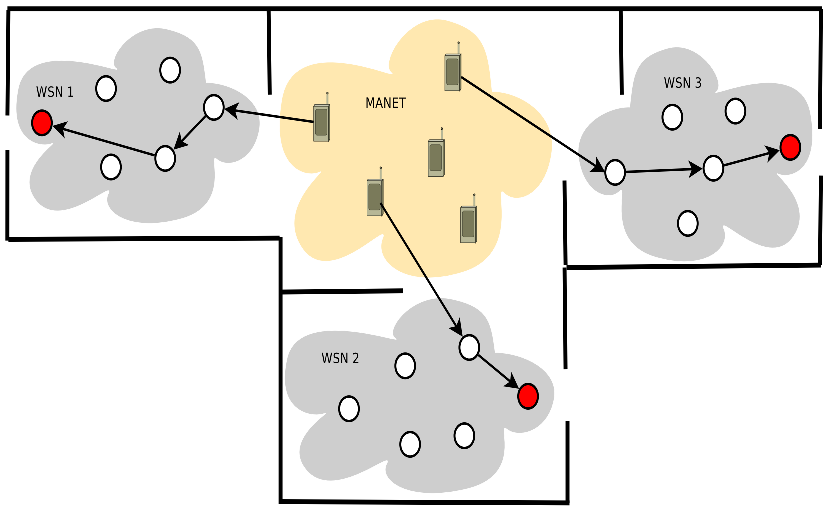

Figure 1. Communication from PDAs to designated WSN nodes

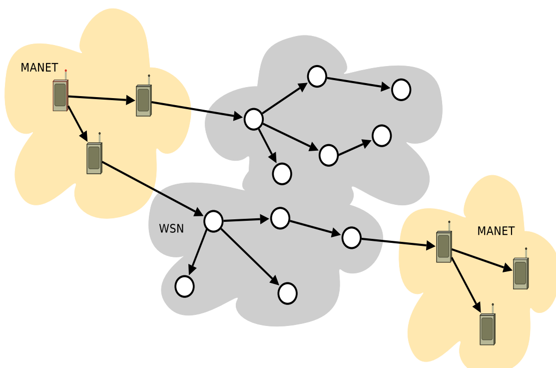

Figure 2. Emergency flooding through multiple networks

results of the simulations and experiments we made. Related work can be found in section 4. We finish with conclusion and future work in section 5.

2 A Routing Protocol for Mobile Heterogeneous Networks

2.1 Requirements

Our scenario produces a number of requirements for the routing protocol:

ID-based Addressing To communicate with nodes in the immediate vicinity a local broadcast is enough. To communicate with distant nodes, a geographic approach might be considered good. But GPS does not work inside buildings, and GPS receivers are still too expensive, if nodes should be used in large quantities. Other localization algorithms are not accurate enough or take too much time. A data centered approach is not useful either. A firefighter that looks for the way out of a burning building will not be interested in the heat levels from all nodes in the building. Rather, only the nodes that are near a certain exit or on the way there are of interest. Therefore, we choose to use ID-based addressing. When the firefighters drop nodes, their ID is recorded automatically, or even preprogrammed before entering.

Support for Heterogeneous Networks and Architectures Due to the scenario, communication must be possible between hand held devices and sensor nodes. We assume that the sensor nodes are equipped with a cheap communication module which supplies only basic functionality with little bandwidth and low data rate. The PDAs on the other hand use wireless LAN to communicate among each other and a zigbee radio module to communicate with the sensor nodes. This leads to a number of problems that have to be solved, e.g. the different size of basic data types (8 or 16 bit for an integer) or the internal representation of bytes (big or little endian).

Ad-Hoc Topologies and Mobility While the Sensor nodes are assumed to be immobile, the firefighters are moving through the burning building (that is their job after all). This means that the logical topology, which denotes the topology determined by radio neighborhood, is constantly changing. While the connections between sensor nodes are assumed to be fairly static, the connections between sensor nodes and firefighters' PDAs change often, as do those between firefighters.

Low Overhead for the Sensor nodes All sensor nodes currently available have severe resource limitations. This is valid for the memory (e.g. 10kB of Ram and 48 kB of Rom on a TMote Sky) as well as for the communication bandwidth and the energy reserves. All these make designing a routing protocol for wireless sensor networks much more challenging then designing one for traditional networks.

Limited Unicast and Broadcast To enable efficient collective operations it is necessary to supply the ability to address a single node within a certain range of hops (Unicast) and to distribute messages to all nodes within a certain number of hops (n-hop Broadcast). For efficiency purposes it is also useful to enable different forms of broadcast for the PDAs. As they could distribute a broadcast over different networks, it is possible to transmit only into one of them (WSN/Manet) or into both.

Tolerance for Asymmetric and Unidirectional Links Experiments with real networks e.g. [12] have shown that asymmetric and even unidirectional links are quite common in wireless sensor networks. Therefore, a way of dealing with them has to be found.

2.2 Different Approaches to Connect Different Networks

There is a number of different ways to connect heterogeneous networks. The most prominent method is inter networking as used in the internet. In this approach, there can be any number of different networks (autonomous systems, AS) with different routing strategies, that are connected. But this approach requires all nodes to have an IP-Address. For wireless sensor networks, this approach has been shown to be inefficient, because of the overhead of transmitting a large IP-Header with every message, whereas the payload is often only a few bytes.

Another solution would be to use IP-Addresses for the PDAs, and simple IDs in the sensor network (WSN-ID). This would require the usage of gateways for address translation or heterogeneous addressing, where each sensor node needs to know the IP-Addresses of the PDAs it is communicating with as well as the WSN-ID of its surrounding nodes. This would lead to a lot of memory consumption on the sensor nodes. Also, in the case of communication between WSN and PDAs, the IP-Address would have to be transmitted, in the worst case through the whole sensor network.

A third possibility is to use a unified addressing scheme for both networks, that is based on WSN-IDs. In this case, the IP-Addresses of the PDAs would be ignored, and the unified addressing used on top of raw WLAN broadcast. This has the advantage of reducing the overhead in the WSN.

2.3 The implemented Approach

To minimize the overhead in the sensor network, a flat address space was chosen. The MANET nodes use the same address type as the sensor nodes. Because the PDAs have stronger batteries and a longer range, most of the communication should take place in the MANET. In our implementation the connections between nodes are weighted with a cost metric, which can be individually tuned. Figure 3 shows an example where each connection involving a sensor node is assigned a cost of 2, and pure MANET connections a cost of 1. In this example, the node in the upper left of the sensor net needs to communicate with the one in the lower right. As there is a MANET nearby, this can be used as a communication backbone. The communication through the sensor network would involve 6 nodes for a cost of 12, whereas the communication through the MANET involves 2 sensor nodes , 2 switches between the network and 3 MANET hops, leading to a total cost of 4+4+3 = 11. The difference becomes stronger when the difference of costs is higher.

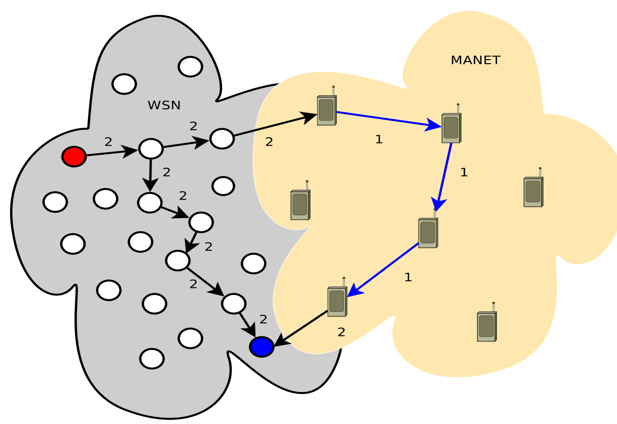

Figure 3. Routing in a weighted heterogeneous network

To further reduce the network load in the sensor network, the addresses are divided into sensor identities and MANET identities. This way, a node always knows in which network the destination can be found. This is also useful to limit the range of multi hop broadcasts inside either the MANET or the sensor network.

In some cases, like the afore mentioned emergency evacuation, a spreading through both networks is wanted. To enable all these different scenarios, the addressing scheme depicted in figure 4 is used. The most significant bit decides if one or both interfaces should be used on a MANET node, on the sensor nodes only one is available. The second bit is used as identifier for the network the destination can be found in. The address of the node takes up the rest of the

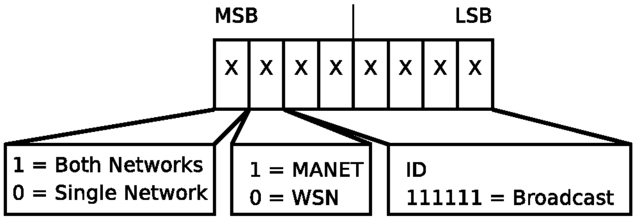

Figure 4. The address field used in our implementation

header, in our example we used 6 bits, enabling up to 63 WSN nodes and 63 PDAs.

In prior work we introduced COPRA [3], a communication processing architecture, where different aspects of communication, like medium access control [9], link layer retransmissions [1] or routing are represented as so called protocol processing stages (PPS). These stages can then be combined to form complete network stacks, so called protocol processing engines (PPE). Figure 5 shows the PPE that we used on the PDAs. The designed routing protocol is connected to a PPS called `WsnUdpGate`. Evaluating the destination address, this stage determines the interface(s) over which to transmit the message: UDP (WLAN), WSN (Zigbee) or both. The message is then forwarded to the corresponding hardware drivers.

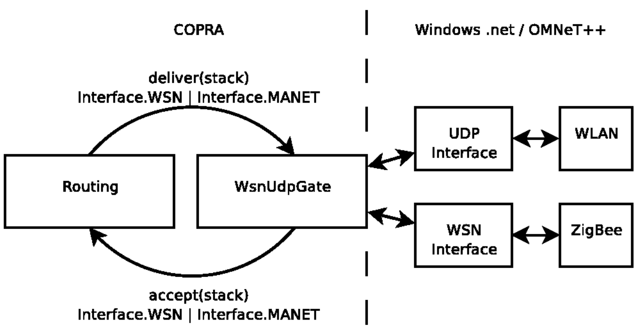

Figure 5. A Packet Processing Engine used on a PDA

3 Simulations and Experiments

To evaluate our concepts we implemented a modified version of Ad-Hoc On Demand Distance Vector Routing (AODV) [11]. In this section some of the results of our simulations are presented, as well as a few real experiments. Due to problems of the manufacturer of the the sensor nodes (MoteIV Corporation), we did not receive the larger number of nodes we ordered in time and were only able to show the functionality of the implementation for the real hardware, no quantitative measurements were possible.

3.1 Simulations

All simulations were performed on a modified version of OMNeT++ [13], which allows the simulation of interacting C++ and C# modules [6]. Mobility and communication have been simulated by means of the INET-Framework, which has also been modified to allow the usage of multiple wireless interfaces on a single node. The enhancement was necessary to enable the simulation of the MANET nodes, which are equipped with a IEEE 802.11 WLAN as well as a Zigbee transceiver. All simulations have been run on 10 randomly generated networks, the numbers shown are averages.

3.1.1 Challenge-Response Scenario

This scenario uses 40 randomly placed stationary sensor nodes and 8 mobile PDAs with changing speeds (figure 6).

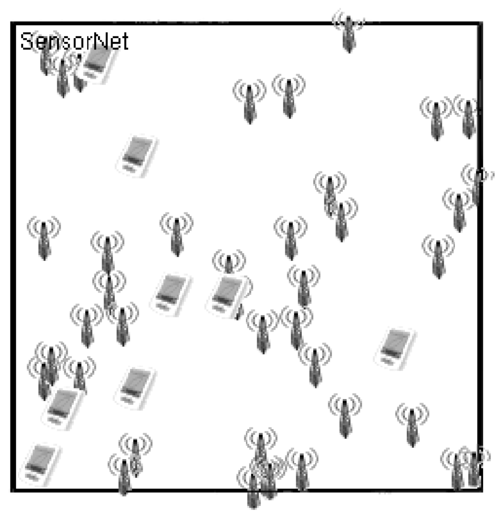

Figure 6. OMNeT++ Simulation of 40 Sensor Nodes and 8 MANET Nodes

Each PDA requested data from randomly chosen sensor nodes, a successful packet delivery was achieved, when an answer from those nodes reached the PDA.

Four different versions of our modified AODV were simulated: Without extension, with intermediate replies, using piggyback mechanisms by attaching data to route request packets and finally using piggyback mechanisms and intermediate replies. The results of our simulations can be found in figure 7. As expected, the versions that use intermediate replies suffer heavily from increased mobility, because

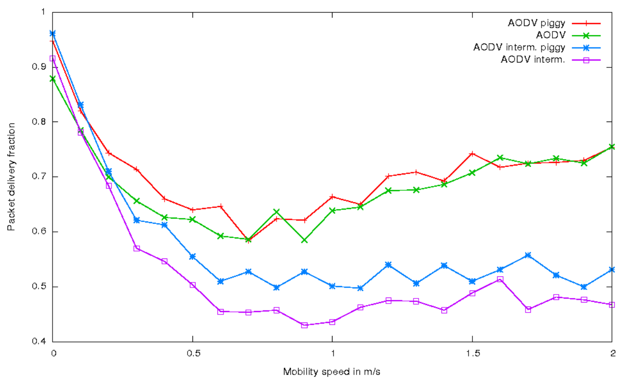

Figure 7. Challenge-Response results

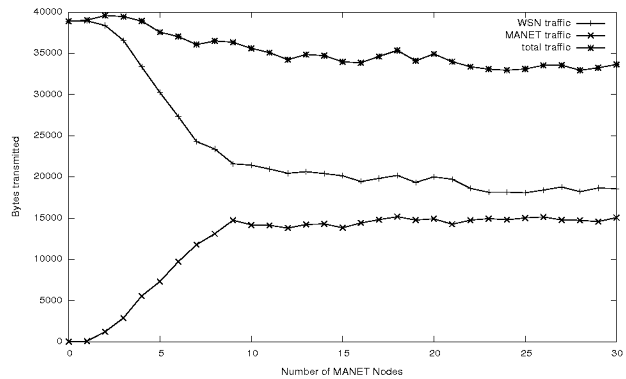

Figure 9. MANET Backbone results

routes that are no longer in existence get propagated. Interestingly, the version where data is sent as piggyback and the version without extensions seem to have nearly the same success rate. In this case, the option of sending data as piggyback should clearly not be used, because of the overhead generated, when flooding the enlarged route request messages.

3.1.2 MANET-Backbone Scenario

In this scenario the gain of routing sensor network traffic over MANET nodes is shown. We simulated a field of 300m times 150m, with sensor nodes 0–3 placed along the left edge and sensor nodes 4–7 on the right. All other nodes, MANET and sensor, were placed randomly in the area in between (figure 8).

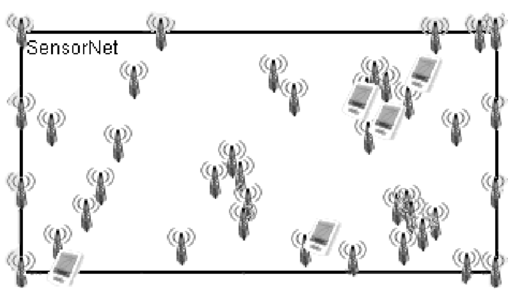

Figure 8. Simulation of a MANET Backbone

The network load is measured in total bytes sent, divided for MANET and sensor nodes. The first simulation consists only of sensor nodes. Then, in each following simulation, one sensor node is replaced by a MANET node, until only MANET nodes and the 4 sensor nodes on each side remain. Figure 9 shows the results of our simulations. As the cost associated with a MANET hop was one, but the one for a WSN hop 2, the routes that were chosen consisted more and more only of MANET nodes, as more MANET nodes became available. The number of bytes transmitted by the sensor nodes decreased, which would lead to less energy consumption in these resource constraint devices. While the number of bytes transmitted by the MANET nodes increased, this is not much of a problem, as the batteries of the PDAs could be easily replaced in the field, which is not possible in case of the sensor nodes. Also, the total number of bytes transmitted in the network decreased slightly.

3.2 Experiments

For our experiments we used Tmote Sky sensor nodes from MoteIV Corporation (figure 10). Since we did not

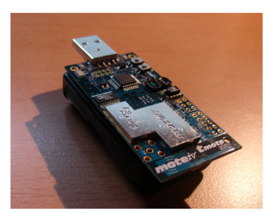

Figure 10. A Tmote Sky sensor node used in our experiments

have a large number of Tmotes available, we performed only four different experiments, to prove the general functionality of our approach. Quantitative measurements were not possible.

3.2.1 Single Hop

The first experiment featured only one laptop and one Tmote. Since the Laptop did not have an IEEE 802.15.4 transceiver, a second Tmote was attached to its USB port and used as a IEEE 802.15.4 modem. Then a simple ping-pong application was used.

Table 1. Single Hop Scenario results

packets	delivery ratio	RTT min	avg	max
100	94%	103 ms	299 ms	537 ms

Table 1 shows the results of our measurements. The 6% packet loss can easily be explained by collisions between route request- and acknowledgement packets. These experiments were only meant to show that communication was possible at all, but also already hint at a possible problem: due to the usage of the Tmote as modem for the laptop, the difference between minimal and maximal round-trip-time (jitter) is very high.

3.2.2 MANET-MANET-WSN

The setup of the second row of experiments featured the Tmotes and two laptops, one of which again used another Tmote as modem. The layout of the experiment can be seen in figure 11. The laptop on top wanted to communicate with the sensor nodes, using the laptop on the middle as a gateway.

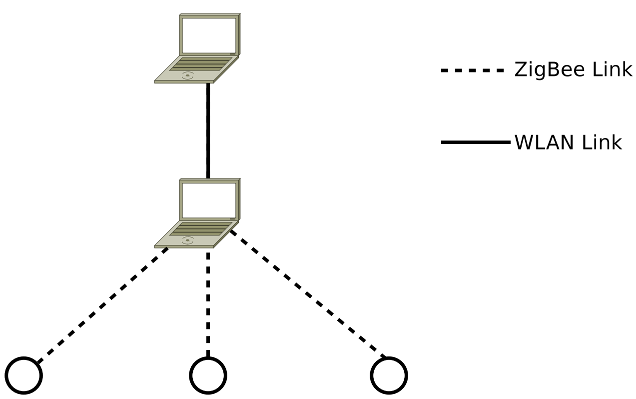

Figure 11. Ping-Pong scenario setup

The results of these experiments are depicted in table 2. It can be seen that he additional MANET hop increased the round-trip-time by at least 95 ms, up to 284 ms. This seems to imply (as will be shown later) that the transition between networks and the communication on the laptop takes much more time than that between Tmotes.

Table 2. Measured round trip time Ping-Pong Scenario

packets	delivery ratio	RTT min	avg	max
100	92%	198 ms	498 ms	821 ms

3.2.3 WSN-MANET-MANET-WSN

The third row of experiments featured communication between two Tmotes, using a MANET tunnel in between. In figure 12 the sensor node on the left side wanted to transmit to the senor node on the right side. As they were not within range, communication was only possible using the WLAN of the laptops in between.

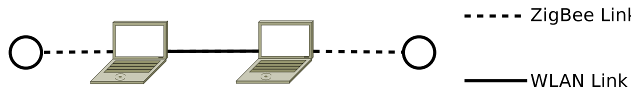

Figure 12. Tunnelling WSN packets through a MANET

Table 3 shows the achieved packet delivery ratio and round-trip-time. Note, that for all experiments no MAC layer was used. While this was no problem for those depicted above, it was devastating for this setup. The rate of 86% was only achieved by disabling the data packets, because they kept colliding with the next route request.

Table 3. Results of the tunnel scenario

packets	delivery ratio	RTT min	avg	max
100	86%	310 ms	514 ms	770 ms

3.2.4 WSN Multihop

In this last row of experiments only Tmotes were used, which were arranged in a row of 2, 3 or 4 nodes. Table 4 shows the results of these experiments. As suggested earlier, the communication between Tmotes is fairly fast, and the jitter is fairly low. Each hop seems to add about 30 ms to the round trip time.

Table 4. Measured multihop round trip times

hops	delivery ratio	RTT min	avg	max
1	97%	20 ms	29 ms	30 ms
2	81%	50 ms	56 ms	60 ms
3	94%	70 ms	87 ms	100 ms

4 Related Work

The idea of adding firefighters with sensor networks has been proposed in different ways. Sometimes the sensors are used to find trapped people or to monitor the health status of the firefighters themselves [4]. Siren [2] uses a tuple-space like abstraction to exchange data about measured heat values between firefighters. The main difference between their approach and our is that we determine the heat levels from a distance, whereas in theirs one of the firefighters must have received the values directly, before forwarding them to his colleagues.

The authors of [7] introduced TEEN and its successor APTEEN [8]. Teen is a hierarchical cluster based routing protocol for wireless sensor networks. In this protocol, sensors are gathered in groups (so called clusters), with one of them as leader (cluster-head). Communication inside these groups always takes place between one of the nodes and the cluster-head. Communication between different clusters is possible only from one cluster-head to another. In our approach the higher cost assigned to the hops between sensor nodes leads to more of the communication taking place between the PDAs than between sensor nodes. If the number of PDAs is high enough, and there is always a PDA within reach of any sensor node that wants to transmit, the PDAs would behave like the cluster-heads in TEEN.

The routing protocol AODV, which was modified for this work was introduced in [11]. It was intended as a protocol for MANETs, and is in its original form too heavy-weighted to be used in sensor networks. However, with the modifications we made, we were able to adapt it to run on a Tmote Sky without running into memory or energy problems.

Many other routing protocols for sensor networks use different metrics. These include among others the hop count, the minimal energy consumed along the way or the remaining energy of each node [14, 10], or the load on particular nodes, to name but a few. Our approach also keeps in mind the energy constraints on the sensor nodes, but not focused on the single sensor nodes. Rather, our approach tries to shift as much traffic as possible to the much stronger (larger battery, higher bandwidth, greater range) PDAs.

5 Conclusion and Future Work

In this paper we have presented a combined routing protocol for sensor networks and WLAN based MANETs. The proposed approach uses weighted connections between nodes to determine which path to take. We have deliberately chosen a simple metric that is not hard to compute and can easily be implemented on resource constraint sensor nodes, too. The results of our simulations show the advantages of this approach and the feasibility of the approach has been demonstrated using a prototype implementation on Tmote Sky sensor nodes and laptops. However, more research with a larger number of nodes is clearly necessary. In the future, we would like to combine this routing protocol with the collective operations of COCOS [5], a high level middleware layer that provides data parallel operations on entire groups of sensor nodes.

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