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Opportunistic Distance-aware Routing in Multi-Sink Mobile Wireless Sensor Networks

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Abstract: Wireless Sensor Networks are a research area of growing importance within the Wireless Networks research community. One of the major issues in this area is the search for efficient routing methods. Most of the routing algorithms developed so far are limited to single-sink scenarios with no or limited mobility. This paper presents a new routing approach, ODEUR (Opportunistic relative Distance-Enabled Unicast Routing), that is targeted to Sensor Networks with mobility-induced intermittent connectivity and multiple alternative sinks as it is often seen in wildlife or habitat monitoring applications.

Keywords: Opportunistic routing, wireless sensor networks, multiple sinks.

1. Introduction

Wireless Sensor Nodes are an exciting topic of research for several years already. The vision of having autonomous devices being capable of sensing, processing and communicating, while being as large as a coin and costing less than one Euro, is challenging and opens new application fields, like wildlife and habitat monitoring, environmental monitoring and smart home and office applications.

Efficient and reliable routing is an essential issue in Wireless Sensor Networks (WSN). For routing, Wireless Sensor Nodes need to take the specific requirements of the application into account, i.e. in many cases energy-efficiency and maximum lifetime. In some application fields there is a high density of nodes, but in others there is only an intermittent connectivity between source and destination. The latter case is considered in this paper. Typical applications would be wildlife monitoring, but also emergency response applications, where devices and people are equipped with sensor nodes.

The need to optimize energy consumption by minimizing the protocol overhead has lead to a vast number of routing algorithms which minimize energy consumption and maximize network lifetime. The utility of the protocol overhead is particularly critical in scenarios with unpredictable mobility of nodes which have to act as multi-hop relays. The problem of the resulting intermittent connectivity is addressed with the opportunistic routing.

Opportunistic routing, as the name implies, is a routing mechanism that looks for the best opportunity to forward a message towards the destination also in the absence of a connected end-to-end route. It is performed on a hop-by-hop basis where the best next hop is selected according to the protocol-specific criteria. Due to this hop-by-hop decision making characteristic, an opportunistic routing protocol does not require a stable end-to-end connection from the data source to the sink, but it can operate in situations in which the topology is intermittently connected and continuously changing. Examples for existing opportunistic routing protocols are Extremely Opportunistic Routing (ExOR) [1], Opportunistic Routing in Ad Hoc Networks (OPRAH) [2] and Region Based Opportunistic Routing [3], but not all of them are suitable for Wireless Sensor Networks. OPRAH for example uses the promiscuity of the air interface to overhear other transmissions, so it is stated in the OPRAH publication that it has a relatively high power consumption which does not fit to the WSN constraints mentioned above. An opportunistic routing approach for WSN that is designed for similar conditions as the one presented in this paper is the Delay/Fault-Tolerant Mobile Sensor Network (DFT-MSN) [7]. However, the routing approach shown there is quite different to the one presented here.

In this paper, a new opportunistic routing algorithm, ODEUR (Opportunistic relative Distance-Enabled Unicast Routing), is proposed and evaluated in a specific network scenario characteristic for the WSN application in wild-life or habitat monitoring.

This paper is organized as follows. In section 2, the investigated WSN scenario is introduced. The proposed ODEUR algorithm is described in section 3. In section 4 the applied simulation model is presented and the results obtained in the simulation study are evaluated. Section 5 concludes the paper.

2. Sensor Network Scenario

The study presented in this paper focuses on the technical scenario which is an abstraction of a real world WSN application for wild life or habitat monitoring with two types of mobile nodes: the sensor nodes attached to the animals, and the sinks nodes carried by the rangers or farmers. It is assumed that the sinks nodes are superior to the mobile nodes in terms of power and memory/processing capabilities. For them, power consumption is less critical than for the sensor nodes because they can always be recharged when the ranger/farmer returns to his base. Furthermore the density of nodes (animals, rangers) will be low in comparison to the transmission range. An end-to-end connectivity will not always be there.

The information collected is not time critical and communication can therefore be non-real-time, or delay-tolerant.

In the investigations presented here, it is further assumed to have a multi-sink data-collection scenario with mobility. The network consists of a number of sensor nodes ($n_{sensors}$) and a number of sink nodes ($n_{\sin ks}$), where $n_{sensors} > n_{\sin ks}$. All nodes are considered to be mobile, including the sinks. The movement of nodes is constrained within a rectangular bounded area (D × D), and is modelled with the random direction model [4], where each node moves in one selected direction until it reaches the boundary, and then selects a new direction and a new speed randomly from the feasible range, so as to stay within the simulation area.

All sinks are considered to be equivalent in their functionality at all layers (e.g., as organized within a peer-to-peer network themselves) so that the sensor nodes can send their data to any of the sinks, leveraging sink diversity.

The communication range (R) of sensor nodes is smaller than their maximal distance within the simulation area ($R < D\sqrt{2}$). Communication between two nodes is possible if the nodes are close enough to each other, i.e., at the distance less than R; if they move out of communication range, the connection breaks, thus leading to intermittent connectivity.

Due to their superior capabilities, the sink nodes can periodically transmit beacons at a power level that is higher than the sensor node communication power. This provides the possibility for sensor nodes to obtain some information from the sinks, i.e., to hear from the sink nodes, even though these are out of their (transmission) communication range. Figure 1 illustrates the general aspects of the scenario.

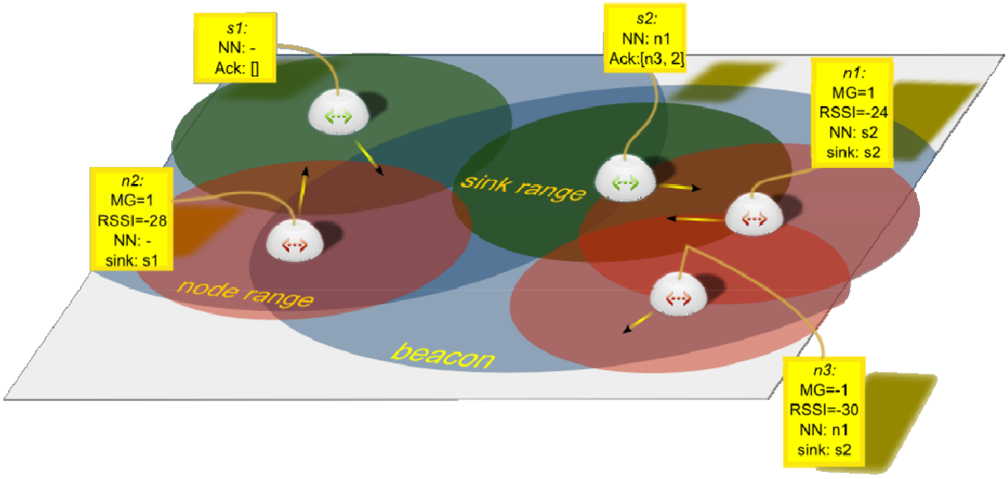

Figure 1: Scenario illustration

3. Routing Algorithm Outline

Due to the intermittent connectivity which is characteristic for the presented scenario, a connected end-to-end path, i.e., a valid route, between a sensor node and a sink may not exist at all time, and an opportunistic routing protocol based on delayed hop-by-hop forwarding is needed. Instead of calculating a route, a node acting opportunistically will judge whether it is sensible to forward its data to another node in its vicinity. The decision to forward a message can be based on different types of information. In the presented approach the decision is made based on the inferred knowledge about the nodes' current position and movement relative to a sink (sinks), and relative to other nodes in its temporary neighborhood. The ODEUR (Opportunistic relative Distance-Enabled Unicast Routing) proposed here is based on two measures: the Received Signal Strength Indication (RSSI) and the mobility gradient (MG). RSSI is a power level (usually in dBW) that indicates the received power of a sink beacon, i.e., the relative distance to the sink. An RSSI threshold is defined as a minimum RSSI required to be able to communicate. Based on the periodic tracking of the RSSI level a node can calculate the mobility gradient MG as a measure of the node movements relative to a sink. In the current version of ODEUR the mobility gradient can have 3 values:

- MG = 1 if the node moves towards the sink,
- MG = 0 if the distance to the sink is constant,
- MG = -1 if the node moves away from the sink.

The node's relative movement is detected by analyzing the difference between consecutive RSSI values. As varying channel conditions and noise usually induce some variation in the RSSI values, a variation threshold is defined. This threshold is used in the mobility gradient MG = 0 case, as otherwise, the mobility gradient will be continuously changing.

If a node is out of communication range of a sink and another node is in a more advantageous position, the nodes have to obtain knowledge about this in order to be able to act as multi-hop relays. Therefore, the sensor nodes use a so-called beacon forwarding: upon reception of a sink beacon, they create own beacons in which they include the sink address of the received beacon and their value of the RSSI they receive from the respective beacon and their relative mobility to this beacon (mobility gradient value). The forwarded beacons are transmitted with normal power. Received forwarded beacons are not forwarded further. This has two reasons: firstly, beacons forwarded over more hops can not provide a reasonable mobility gradient value, and secondly, a limitation of beacon forwarding is required to keep the algorithm scalable in large scenarios. To avoid collisions caused by simultaneous beacon forwarding, a random beacon forwarding is used according to the formula

$$t_{forward} = t_{now} + t_{wait} + rand(0.1)$$

where $t_{forward}$ denotes the beacon forwarding time, t_{now} is the current time, t_{wait} is a fixed waiting time to collect several beacons that come in short sequence. The last term in the formula is a random value drawn from a normal distribution, here with a mean value of 0.1, and other mean values being possible as subject to further protocol tuning. Simulation experiments have shown that the beacon forwarding delay can significantly reduce the collisions in the network.

All received beacons are used by the receiving node to set up a table of the neighborhood information. This table contains all available neighbor nodes (those with an RSSI value larger than the RSSI threshold) and the respective RSSI and mobility information. The information in the table has a limited lifetime, if no beacon has been received from a node for longer than an entry expiration time, the entry is eliminated. From this table, the node with the most favourable conditions can be elected as Best Neighbor Node (BNN) if it is reasonable to forward data through this node. It is elected under the following conditions:

- Source node (SN) MG_{SN} = -1 or MG_{SN} = 0 and neighbor node (NN) MG_{NN} = 1,
- MG_{SN} = -1 and MG_{NN} = 0 and $RSSI_{NN} > RSSI_{SN}$,
- MG_{SN} = -1 and MG_{NN} = -1 and only the neighbor node is in sink range,
- Both nodes are in sink range and $RSSI_{NN} > RSSI_{SN}$.

If any of these conditions hold, the data is routed to the BNN. Otherwise, the SN either keeps the data (if it has no neighbor or is moving towards the sink). If the sink is in a communication range of the node the message will be sent directly to the sink.

4. Simulation

The simulation of the ODEUR algorithm was done in the network simulator OPNET [6]. As shown in Figure 2, the implementation is based on the publicly available MAC (Medium Access Control) and PHY (Physical) layers from the Open-ZB IEEE 802.15.4 stack implementation (version 1.0) [5] which was used with two modifications in the MAC layer: the PAN-coordinated mode was replaced by an ad-hoc mode with unslotted CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), and a transmit power control was added which is needed to send the high-power sink beacons.

On top of the MAC layer, a new network layer running the ODEUR protocol is implemented including the mobility gradient calculation, BNN selection, and beacon forwarding.

The application layer contains some basic applications: the sink application provides statistical evaluation of the data received at the sink, the beacon application creates the sink beacons and the data application generates the data packets to be sent.

Apart from the protocol layers, the model also contains a power consumption model, realized within a battery module which is tracking the transmission and reception power consumption on the air interface. The battery model is taken from the Open-ZB model and is based on the characteristics of MICAz motes.

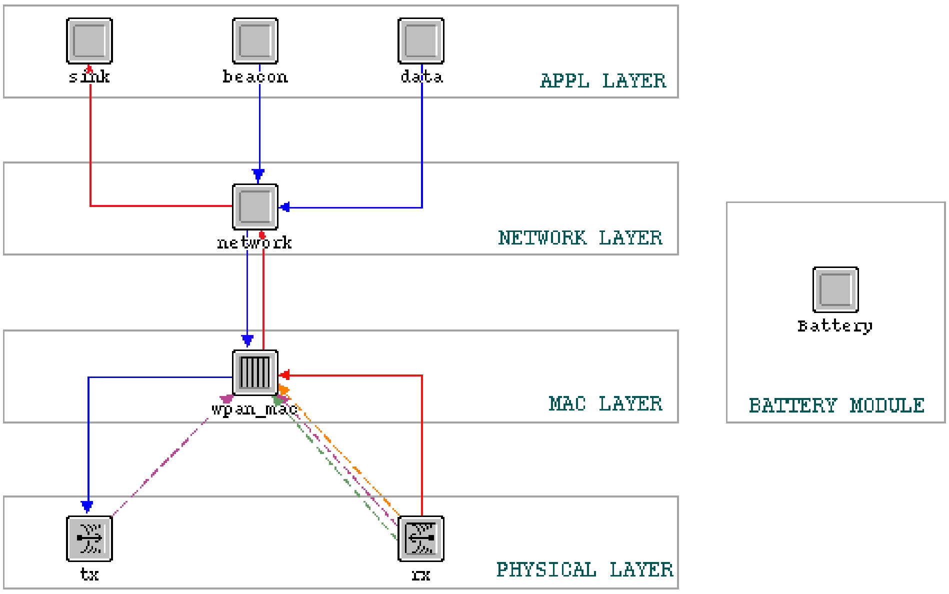

Figure 2: Node model in OPNET

The concrete WSN scenario evaluated in OPNET (Figure 3) contains 3 sink nodes and a number of sensor nodes, which varies in the range [5..25]. The dimensions of the simulation area are 100m × 100m. All nodes move according to the random direction mobility model [4], their speeds are chosen randomly between 1 and 5 m/s, and they are pausing for a random pause time of 5 to 10 s at the scenario borders.

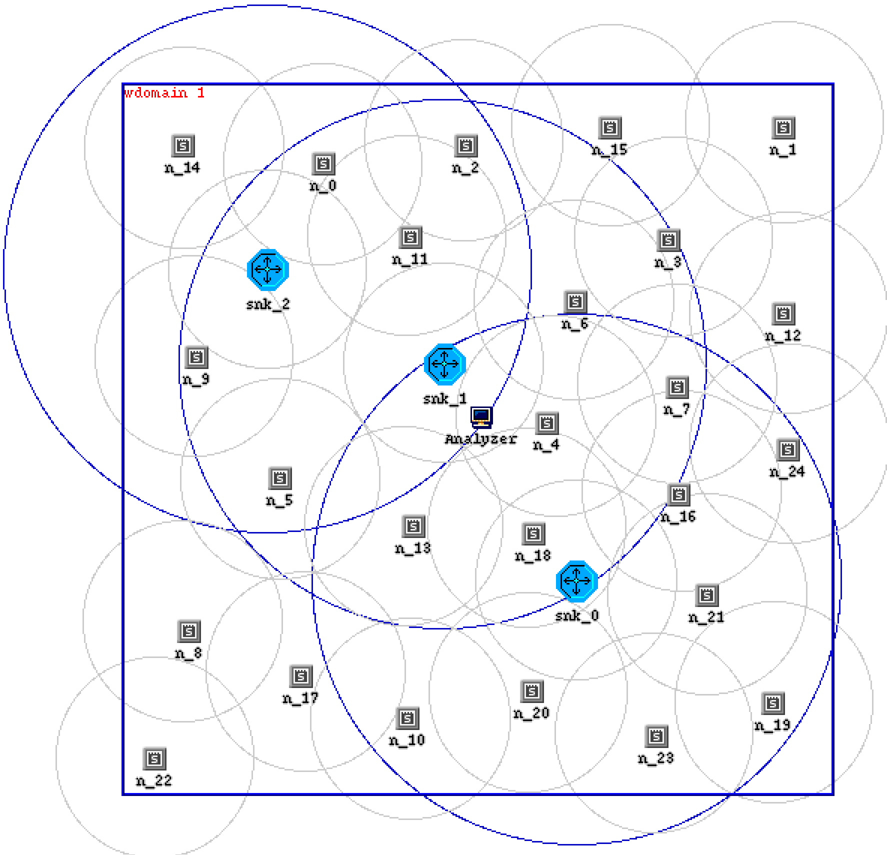

Figure 3: WSN scenario in OPNET

The RSSI threshold is set to -143 dBW. This power level was determined through simulation as the one required for a sufficiently reliable transmission in the OPNET model.

For the transmission power, three different power levels are used (corresponding communication range in brackets):

- $1*10^{-8}W$ (14.038 m)
- $4*10^{-8}W$ (28.076 m)
- $7*10^{-8}W$ (37.141 m)

The sinks use a power multiplicator of 7, so that the corresponding beacon power levels range from $7*10^{-8}W$ to $4.9*10^{-7}W$. The beacon period is 1 s, and data packets are generated at one node with a size of 256 bits and an interpacket interval of 5 s, thus leading to a data rate of 51.2 bits/s. The entry expiration time for the neighbor tables is set to 120% of the beacon period.

When comparing the (cumulative) traffic sent with the traffic received, it can be seen that the intermittent connectivity leads to a bursty packet arrival at the sink, but eventually (also due to no memory constraints assumed at the nodes), practically all packets reach a sink (see Figure 4). Figure 5 shows how the total received packets are shared between the sinks. It can be seen that each of the sinks receives some parts of the traffic. This can be regarded as proof that the algorithm works as expected. Further performance characterization is presented in the next section.

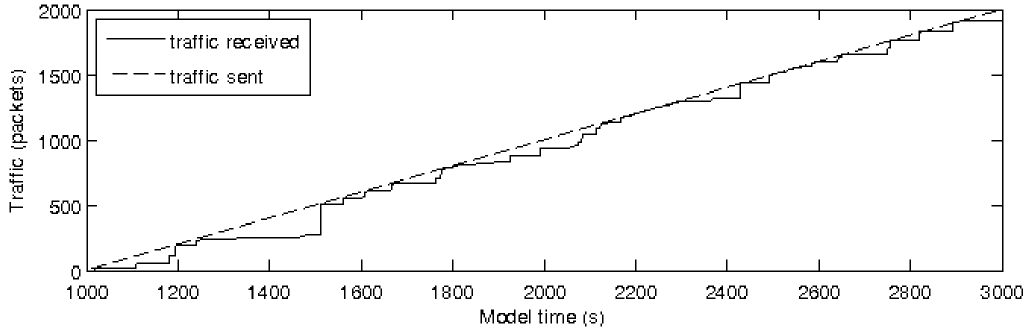

Figure 4: Sent vs. received traffic

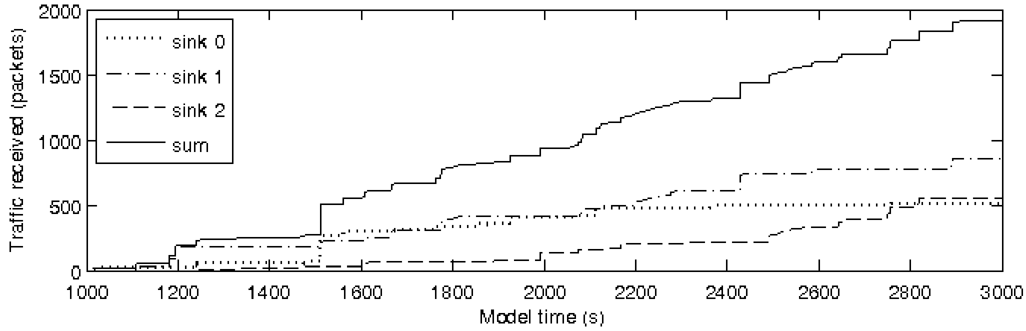

Figure 5: Received traffic per sink

4.1 – Performance Evaluation and Comparison with AODV

Performance parameters further evaluated are end-to-end delays, route lengths, network load, goodput and power consumption. The results obtained with ODEUR are compared with the results obtained with AODV (Ad-Hoc On-Demand Distance Vector Routing). For this purpose, the existing OPNET model of an AODV-enabled MANET station was modified so that it used the IEEE 802.15.4 PHY and MAC layers instead of Wireless LAN (IEEE 802.11) beneath the network layer. As AODV is not capable of exploiting sink diversity, a single-sink setup was additionally chosen for the ODEUR simulations to compare with AODV under fair conditions.

Tests are performed in three setups: ODEUR with 3 sinks, ODEUR with a single sink, and AODV with a single sink. Some selected results are presented in the following.

Table 1: End-to-end delays

Setup	ODEUR, 3 sinks	ODEUR, 1 sink	AODV, 1 sink
TX power 10 nW	27.29 s	64.055 s	2.149 s
TX power 40 nW	6.223 s	14.380 s	1.550 s
TX power 70 nW	3.499 s	7.454 s	0.882 s

Table 1 shows the end-to-end delays of ODEUR and AODV. These end-to-end delays are values averaged over different network densities. It can be seen that the delays are significantly shorter in AODV, but it has to be pointed out that only the delays of successfully transmitted packets are counted here. Comparing the ODEUR setups with different numbers of sinks, it can be seen that more sinks lead to shorter end-to-end delays as the probability is higher to reach a sink with less hops and in shorter time.

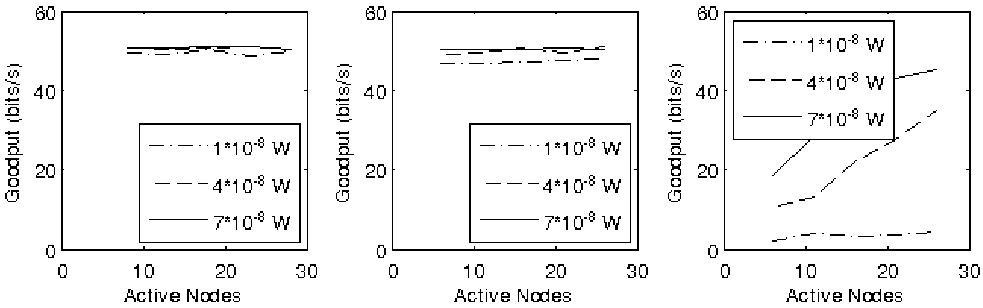

Figure 6: Goodput results for: ODEUR, 3 sinks (left); ODEUR, 1 sink (middle); AODV, 1 sink (right)

The seemingly bad performance in the end-to-end delays is put into another perspective if the goodput is regarded additionally. The comparison in Figure 6 clearly shows that in ODEUR, the packet loss is negligible, while AODV shows a very poor goodput in case of low transmission power and few network nodes, i.e. in scenarios where intermittent connectivity appears frequently. The reason is that AODV is simply not able to establish reliable end-to-end routes in those cases.

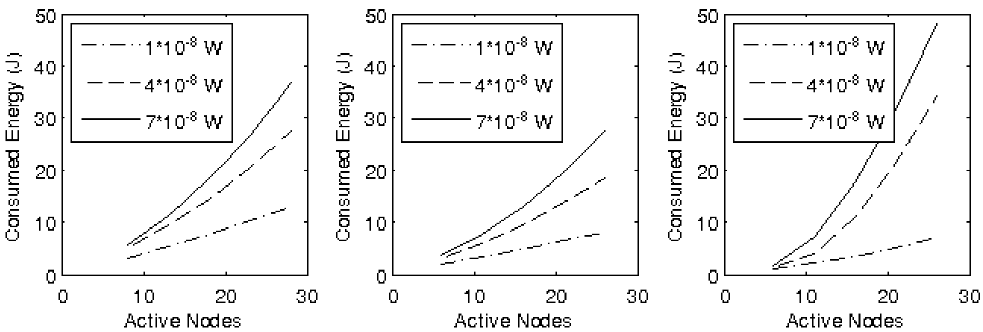

Figure 7: Power consumption for: ODEUR, 3 sinks (left); ODEUR, 1 sink (middle); AODV, 1 sink (right)

Figure 7 shows a comparison of protocols with respect to the overall energy consumption in the network. It can be seen that, as soon as AODV reaches conditions where it can operate, it requires more power than ODEUR. Additional sinks in ODEUR lead to an increase in the power consumption as there are more beacons to be forwarded.

5. Conclusions

A new opportunistic routing algorithm for sensor networks, ODEUR, was presented. This algorithm has proved to be a promising routing approach for multi-sink wireless sensor networks. It has outperformed the AODV algorithm, especially in terms of a guaranteed reception of sensor data at the sink(s). The algorithm has most advantages if it is used in a scenario with frequently intermittent connectivity and where short end-to-end delays are less important than a guaranteed reception of the sensor data.

Further work will focus on extensions and refinements to the algorithm, including power control mechanisms to reduce the transmission power under good conditions, data aggregation and extension of the mobility gradient to include the node's speed. Additionally, extensions to allow end-to-end acknowledged transmissions will be done. Comparisons to other opportunistic routing schemes, e.g. the DFT-MSN [7], are planned.

In a later step towards efficient resource usage, it may also be reasonable to investigate on the potential of cross layer optimisation between the MAC and network layers, and finally also between the network and application layers to integrate context-awareness with respect to the application context.

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