Mobility to improve efficiency of data collection in wireless sensor networks

Mona Ghassemian
Computer and Mathematic Science Department
University of Greenwich, UK
Email: m.ghassemian@gre.ac.uk

Hamid Aghvami
Centre for Telecommunications Research,
King’s College London, UK
E-mail: hamid.aghvami@kcl.ac.uk

Abstract

In mobile communication environments, traditional routing protocols designed for static wireless sensor networks may fail to deliver data timely. The aim of this work is to identify improvements that can be obtained considering mobility and to recognize its research challenges. We briefly describe different levels of mobility in wireless sensor networks (WSNs) and highlight the efficiency of routing in the presence of the mobility.

1. Introduction

Typically wireless sensor networks have been considered to be deployed by static sensor nodes (SNs). In this paper we discuss that the static paradigm may be expanded by introducing mobility for specific application scenarios. Mobility has traditionally been viewed as adding complexity to the design of wireless networks, e.g., cellular handovers, frequent location and routing updates. This introduces an additional dimension to WSN research challenges across the different communication layers.

A typical solution to maintain connectivity is to use long-range communication interfaces which can be very expensive for sufficiently large areas. The role of mobility in the static sink scenarios is to maintain connectivity without utilizing many relay nodes. The effect of mobility is often considered to affect on the accuracy and complexity of WSN protocol. In this paper we present the research suggesting that mobility can help improve the performance of the designed WSN protocols in different layers. When sensor nodes detect an event there are two main proposed solutions to relay the data to a sink node.

One proposed solution is that the sensors themselves may be moving and collecting information, for instance SNs’ carriers constantly change their location and/or orientation to monitor [2], [4], [9]. For any policy that does not use relays, sensor nodes travel towards sink node(s) to deliver their data. Secondly relay techniques (so called routing algorithms) can be applied to route the event messages from the sensor nodes to the sink node. Examples for these protocols are LEACH and Direct Diffusion.

The first proposed solution requires all the sensor nodes to be mobile. The limited power resources for sensor nodes should perhaps be more efficient to be used for data sensing and transmission rather than generating energy for mobility of the nodes.

The second solution adds complexity (packet header or signalling overhead, routing table setup and maintenance) to the network which degrade the scalability and energy efficiency of the data relaying. In WSNs with stationary sink nodes where the collected information is sent to the sink nodes’ constitute central locations. The high level of concentration causes depletion of energy supplies of sensors in the vicinity of the static sink node, leading to disconnection of the sink node from the network.

This paper aims to raise issues on the effect of mobility as a new dimension to the static wireless sensor networks. The rest of the paper is summarized as follows: Section 2 defines a mobile data collector solution and application. Section 3 discusses the protocol efficiency in terms of buffering mode, energy efficiency, message latency and multi-hop communication. Section 4 summarises our observations and Section 5 provides further related research areas.

2. Mobile data collector solution and application

We have discussed in Section 1 two possible solutions to relay data from SNs to a sink node. Another proposed solution uses a mobile sink node so called mobile data collector (MDC) that gathers information from sensors by visiting them and finally relaying the collected data to the sink node.

One application scenario for MDC can be identified in farms where a MDC can be placed for instance on a machinery and collects the data measured by the sensors located in the field. We must note that MDC solution is suitable for delay tolerant network applications.

The idea in this solution is that data should be buffered at source SNs until the MDC visits the sensors and
downloads the information over a single-hop wireless transmission. Therefore MDC is a mobile node that changes its position during operation time. The key characteristics of a MDC are large storage capacities (relative to sensors), rechargeable power, and the ability to communicate with the sensors and sink nodes.

A scenario example depicted in Figure 1 shows two mobile data collectors that travel within the sensor field and collect the information that is generated and buffered by each of the SNs. This solution can be particularly beneficial for sparse deployment scenarios that suffer from connectivity problem. The main problem for this solution is the large latency which is relative to the travel time and trajectory of the MDCs. Applying more than one MDC can reduce the message delay and improves the reliability of the message delivery. However duplicate data may be delivered by the MDCs to the sink node.

Figure 1: A model for two mobile data collectors to collect the information from sensor nodes in a wireless sensor network.

3. Efficiency measurements

We briefly discuss the static sink and mobile relay level mobility scenarios in this section. Later in this section we discuss the impact of the mobility of MDC in a static sensor network environment on the performance of the protocols in terms of power efficiency, message latency and buffering type.

A. Data delivery performance comparison of routing and MDC solutions

In static sensor networks, as the collected data from all the sensor nodes are forwarded towards sink nodes, nodes closer to sink nodes transmit more traffic compared to the other nodes further hops away from the sink node. This will eventually result in disconnection since the nodes around the sink node die faster than the rest of the nodes in the network. One solution is to exploit MDCs to carry information between isolated parts of WSNs. Furthermore in the static sensor network it was argued that the best route from any SN to the sink node is the one that carries information over the fewest hops. The same reasoning suggests that a mobile relay level scenario can achieve fewest-hop routes in comparison to the sensor level mobility scenario.

Information carried by the MDC can reduce the energy consumption of sensor nodes by reducing multi-hop communication. However this is not true for all scenarios. A quick way to estimate the effectiveness of the use of a MDC for a given scenario relies on the number of relaying nodes which can be reduced when an optimally placed fixed sink is replaced by a MDC. The network power consumption can be obtained by summing up the power consumed by all nodes. If node \( i \) sends its data over \( H \) hops, then the expected network power spent is given by

\[
P_{\text{net}} = \sum_{i=1}^{n} (P_{\text{hop}} \cdot H_i) = P_{\text{hop}} \sum_{i=1}^{n} H_i = P_{\text{hop}} \cdot n \cdot E[H]
\]

where \( P_{\text{hop}} \) is the power consumed in sending data over a single hop, \( n \) is the number of sensors and \( H_i \) is the number of hops that the data from the \( i \) th SN must travel to reach the static sink node. For a network with \( n \) nodes, the power consumption depends on the expected number of hops alone since \( P_{\text{hop}} \) is decided by the range, which depends on considerations of connectivity. Therefore mobility can save power in a multi-hop sensor network if the expected number of hops to the MDC is less than the expected number of hops to the sink node. Therefore the effectiveness of using mobility to save power depends strongly on the mobility pattern and the transmission range necessary to collect data from the entire network.

Another aspect of the protocol performance is scalability improvements that mobility can introduce into WSNs. Gupta and Kumar [6] showed that in a wireless multi-hop network, throughput per source-destination pair goes to zero like \( 1/\sqrt{n} \) (\( n \): number of nodes per unit) considering nodes stay static for the duration of communication.

It should be noted that in this type of communication model with one MDC node, the MDC path is defined to collect data from all SNs directly and hence each packet goes through at most two hops. In the presence of mobility Frossglauser and Tse [7] proved that
mobility increases the capacity of wireless ad hoc networks when nodes move randomly and independently. This idea has not considered delay and therefore matched to delay-tolerant data delivery applications. A long term throughput of $O(1)$ per source-destination pair can be achieved if a source SN is willing to wait until a MDC node collects its information.

We aim to compare the scalability of the discussed scenarios for data collection with respect to the number of SNs. The mechanism $\beta$ is described more scalable [8] than mechanism $\alpha$ with respect to $n$, if

$$\psi_n \equiv \lim_{n \to \infty} \frac{X_{\text{throughput}}(\alpha)}{X_{\text{throughput}}(\beta)} \to 0$$

where $n$ is number of SNs, $X_{\text{throughput}}(\alpha)$ and $X_{\text{throughput}}(\beta)$ show the rate of growth of the throughput in static sink and MDC mobility level respectively. If relative scalability factor $\psi_n$ is a positive constant, then both solutions are equally scalable.

<table>
<thead>
<tr>
<th>Mobility level</th>
<th>Throughput approximation</th>
<th>Connectivity support in sparse scen.</th>
<th>Multi-hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Sink</td>
<td>$O(1/\sqrt{n})$</td>
<td>Low</td>
<td>Yes</td>
</tr>
<tr>
<td>Mobile relay</td>
<td>$O(1)$</td>
<td>High</td>
<td>No/Few hops</td>
</tr>
</tbody>
</table>

Table 1: Performance comparison between sensor mobility level and mobile relay node mobility level scenarios.

This result justifies an improved scalability in the MDC node mobility level compare to the static networks. It should be noted that the cost of the improved scalability is hidden in additional delay. A summary of the discussion is presented in Table 1.

B. MDC efficiency investigation

In the mobile relay mobility level we described a MDC that follows a predetermined path in the vicinity of the sensors and stops at specific locations for a limited time to collect data from nearby sensors. In this scenario the sensor nodes are not involved in routing and only nodes which are one hop away from the sink can transmit their data to the sink. In this case buffering of data takes place in the sensor nodes, but is instead directly send to MDCs via potentially multiple hops. A hybrid solution [1] of the described short term and long term buffering methods to collect data by a MDC is the Rendezvous-based solution. In this method MDC is sent to rendezvous points (RPs) close to the path of sensor nodes to collect the data. Data are buffered at rendezvous points until they are downloaded by mobile sink nodes.

For these three buffering strategies a discussion of implications is provided in this subsection concerning message delay, mobility patterns of MDC, energy efficiency and multi-hop communication.

**Buffering mode:** In the defined scenario MDCs should have a larger size buffer compared to SNs. Data generated by sensors can be relayed to MDC with or without long term buffering.

For the case with no buffering in SNs, data will be relayed in a multi-hop fashion to the closest MDC node. If two or more number of MDCs collect data in the field, a message from a SN may be relayed to more than one MDC. A higher layer algorithm needs to be considered for data aggregation in the sink node.

For the case with buffering in sensor nodes, data are buffered at source sensors until the MDC visits the sensors and downloads the information over a single-hop wireless transmission. Buffer size has impact of the efficiency of the data delivery. For a given set of links and reported events, an appropriate buffer size to avoid packet losses should be estimated. Although it is much more complex to model the exact relationship between the buffer size and the loss rate, it is usually sufficient to provide a lower bound (i.e., how large the buffer should be to avoid packet losses with high probability).

SNs buffer the data until the MDC notifies the sets of its vicinity nodes that it has reached a different position and provides information on how packets can be routed to it. It is shown that network lifetime will increase in this model. Long term buffering can also increase the scalability of the network.

**Message delay:** As mentioned earlier both sensors and MDCs have buffers. While small buffers could lead to high packet drop rates, reducing the data success rate, large buffers have an associated penalty in terms of energy consumption, physical size and manufacturing costs.

Message delay has two components – delay on the sensor before a MDC picks up the data sample and the delay on a MDC before it encounters a sink node.

The delay of a packet is the time it takes the packet to reach the sink node after it leaves the source SN and has different components depending on the buffering...
mode: single hop-delay which is constant and independent of number of SNs, and buffer time i.e. the time the packet is stored at the relay while moving. The first component is independent of the number of SNs. The hop-delay is short in long-term buffering since the data is buffered and relayed over a single-hop when MDC is in the neighbourhood of the source SN. On the other hand multi-hop communication makes it possible to collect data from remote parts of the network when data cannot be buffered for long term. The second component exists only for long-term buffering and rendezvous solutions and depends on the MDC path and its speed. If the MDCs traverse over fixed paths, this delay component will be deterministic. While in the no buffering mode data is relayed over multiple hops before being delivered to the MDC, which results in a longer hop-delay component, in the buffering mode the data is buffered for a relatively longer period before in is relayed. Therefore the buffer time is shorter in the no buffering mode in comparison to a buffer mode solution. On the other hand the hop-delay component in the no buffering mode is longer. In rendezvous point (RP) solution the buffering time is shorter in SNs and only the RPs buffers the data. The hop-delay is the summation of a multi-hop communication delay between the SNs and the RP and a single-hop communication between the RP and the MDC.

Shah et al explored minimum buffer sizes that would ensure high data success rate while being cost-effective in [2]. It is proved that the sensor buffer requirements are inversely proportional to number of MDCs and the MDC buffer requirement is inversely proportional to both number of MDCs and sink nodes.

**Mobility pattern:** Pattern of the MDC mobility can be random [2] or deterministic (predictable mobility [3] or controlled mobility [4]). While in a no buffering scenario, a controlled pattern should be applied to minimise the number of hops that the data should be relayed to reach the MDC as well as to efficiently reduce the duty cycle of the SNs, in the buffering mode, any mobility pattern can collect the data buffered. The problem that remains is to identify which mobility pattern can reduce the buffering time, and minimize the message delay. It is observed that exploiting controlled mobility pattern can help in saving energy in WSNs. In the mobile element scheduling proposal [4], a MDC node is scheduled in real time to visit sensors such that no sensor buffer overflow occurs.

In the rendezvous solution, the MDC should follow a predictable mobility pattern to collect the data from the RPs and avoid the buffer overflow.

**Energy-efficiency:** The energy consumption is proportional to the number of hops data is being relayed. Therefore buffering can reduce the energy consumption.

Another factor to save on energy is to apply the mobility information of MDC to adapt the SN sleep time. SNs can go to a sleep mode when the MDC is away from them and transit to idle state when they expect to be in close proximity to the MDC and then into the transmit state for the transmission of their collected data to the MDC.

**Multi-hop communication:** Since the number of hops that carry the data is reduced when a MDC moves and collects the information, the relative scalability of the protocol is expected to be increased. Study in [5] showed that the mobile relay mobility level is extended to utilize multiple MDC nodes to provide scalability of deployment area.

Since the MDC does not stay at a fixed position, the fewest-hop route is time variant in nature, and so is the number of hops. Quite obviously, the best solution is to choose the route which consists of the fewest hops at any time. Therefore for delay-tolerant data delivery, MDC node mobility can significantly increase the throughput capacity of WSNs.

A comparison of the discussed issues for MDC level mobility with, without buffering and rendezvous solutions is summarized in table 2.

<table>
<thead>
<tr>
<th>Class</th>
<th>Mobility path</th>
<th>Long-term buffering</th>
<th>Delay</th>
<th>Energy consumption</th>
<th>Multi-hop relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDC without buffering</td>
<td>Control</td>
<td>No</td>
<td>Low</td>
<td>High</td>
<td>Yes</td>
</tr>
<tr>
<td>MDC with buffering</td>
<td>Rand</td>
<td>Predict</td>
<td>Control</td>
<td>Yes</td>
<td>Med/High</td>
</tr>
<tr>
<td>RP point</td>
<td>Control</td>
<td>Yes:RPs</td>
<td>No:SNs</td>
<td>Med</td>
<td>Low/ Med</td>
</tr>
</tbody>
</table>

Table 2: Comparison of Mobile data collector-based communication proposals

4. **Summary**

We described mobility as an additional dimension for wireless sensor networks (WSNs) in this paper. We discuss that mobility can enhance the performance of the WSN protocols. The paper presents a thorough analysis and discussion of surrounding issues of how the use of mobile data collectors (MDCs) in WSNs can increase the efficiency of data collection towards a sink. It investigates the implications of multi-hop communication in the case no MDCs are used and
provides a discussion centered around three possible cases for the use of MDCs. In the mobile relay mobility level we described a MDC that follows a predetermined path in the vicinity of the sensors and stops at specific locations for a limited time to collect data from nearby sensors. In this scenario the sensor nodes are not involved in routing and only nodes which are one hop away from the sink can transmit their data to the sink and therefore have to contend for the channel access. This model generally results in lower message delay, better energy efficiency and better scalability. This is a result of the number of hops that relay the messages to the MDC nodes.

5. Further research
The initial findings presented in this paper look promising for further exploration of protocol design in this area, based on the presented MDC based approach. Another example for mobility awareness is to investigate and measure the effect of the mobility on the WSN protocol performance optimisation applying a cross-layer [10] design between PHY, MAC and higher layer protocols. The cross-layer design and the information that can be used/shared for such optimisation techniques are our ongoing research topic in this area.

6. Acknowledgment
This paper describes work undertaken in the context of the e-SENSE project, “Capturing Ambient Intelligence for Mobile Communications through Wireless Sensor Networks”. e-SENSE is an Integrated Project (IP) supported by the European 6th Framework Programme.

7. References
[9] V. Kawadia, P.R. Kumar, “A cautionary perspective on cross-layer design,” IEEE Wireless Communications, Feb 2005