Towards the Design of an Energy-efficient, Location-aware Routing Protocol for Mobile, Ad-hoc Sensor Networks

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Abstract. *Developments in wireless, mobile communications combined with advancements in electronics have contributed to the emergence of a new class of networks: Wireless ad-hoc sensor networks. Tiny, smart, network-enabled sensing nodes can be deployed to construct sensor fields that form the infrastructure for various self-adaptive and autonomic applications. In this paper we identify the requirements and properties that still need to be addressed and discuss possible approaches that could be adopted in the design of efficient routing protocols for such networks.*

1. Introduction

Recent developments in wireless, mobile communications combined with the constant advancements in electronics that enable the integration of complex components into smaller devices, have contributed to the emergence of a new class of wireless ad-hoc networks: Sensor networks. Typically a sensor board consists of a number of sensors of different modalities which, when combined with a microprocessor and a low-power radio transceiver, forms a smart network-enabled node. The on-board sensors may be motion detectors, thermistors, light sensors, microphones, accelerometers, magnetometers, humidity and barometric pressure sensors, GPS receivers etc. A sensor network may deploy a huge number of nodes depending on the nature of the application. Such applications include medical services, battlefield operations, crisis response, disaster relief, environmental monitoring, premises surveillance, robotics and more.

Sensor networks are also inherent in the concepts of smart dust [1] and ubiquitous computing [2]. Smart dust technology concerns the design and implementation of networks consisting of tiny, invisible sensing grains that aim to be untraceable in practice. Currently, smart dust motes scale down to $1mm^2$. On the other hand, ubiquitous computing concerns the building of intelligent environments. By placing a processor behind virtually every object, the computers are drawn out of their racks to be seamlessly integrated with the physical environment and form a ubiquitous infrastructure that will monitor and/or support every human activity from the simplest to the most complex one.

In many ubiquitous computing applications there is no fixed, backbone infrastructure to support the nodes and therefore the network must be self-adaptive and autonomous, in essence *autonomic*. In the majority of the protocols presented in this paper, a mobile, ad-hoc, wireless network consisting of homogeneous nodes of equal capabilities is assumed[1]. In this sense, a sensor network has obvious similarities with a traditional ad-hoc network. For the rest of this survey we will use the abbreviation MANETs when referring to traditional mobile, ad-hoc networks, WSNs to denote mobile, ad-hoc, sensor networks and the term *mote* to specifically refer to a WSN's node. However there are some vital differences between WSNs and MANETS, which are outlined as follows:

- Energy efficiency/longevity: Sensor nodes power capacity is restricted because sensor motes may be smaller, battery powered and be required to stay alive for longer periods without any support.
- Scalability: Sensor networks are typically denser and require a larger number of nodes. Some projects claim to attempt to deploy billions of devices, including passive ones.
- Mobility: In some applications like environmental monitoring, motes are characterised by higher mobility and topology changes are more frequent than in MANET nodes.
- Fault-tolerance: Although MANETs are designed to be fault tolerant, extra care should be taken regarding sensor networks. This is because the latter is expected to be able to function even after a large number of node failures, which could be a result of their limited power capability and extended life specification.
- Identification: In contrast to MANETs, schemes that make no use of unique IDs are preferred due to the large number of nodes and the applications, which typically require data multicasting rather than end-to-end communication, therefore avoiding IP usage.
- Cross-layer design: Application-level decisions directly influence the design of the substrate layers. For example, different routing protocols may be required according to whether the application is demand or event-driven.

The rest of this paper is organised as follows: Section 2 briefly presents a WSN architecture and application design issues that are directly linked to the underlying network-layer. In section 3, we classify some basic MANETs routing techniques that could prove to be of help towards the design of a WSNs routing protocol. Section 4 presents algorithms specifically designed for routing over WSNs. In section 5 we consider some location and position aware routing for traditional ad-hoc networks that could form the basis for a new energy-efficient, scalable, location-aware protocol for WSNs. We conclude the paper in section 6 extracting the final conclusions and proposing specific research directions.

2. Sensor Networks Architecture and Design Aims

A sensor field consists of up to several thousands of densely deployed, networked, mobile, sensing nodes. A distinguished node, usually referred in the literature as the *sink*, is responsible for gathering the data collected by the other nodes and forwarding it to the external, fixed infrastructure for further processing or forwarding. The sink may be no different from any other node of the WSN and therefore carry all relevant restrictions, or also may be fixed. According to the most prominent power attenuation model [3,4] when a node s transmits to a node r with power P_s, the power at the point where r lies will be: $P_r = P_s / \|s,r\|^k$ where $\|s,r\|$ is the Euclidean distance between the source and the receiving node, and k is the *distance power gradient*. In the real world, it holds that $2 \le k \le 6$ according to the topology of the space, but for an even, flat surface it stands that

[1] When this does not apply, it will be stated explicitly.

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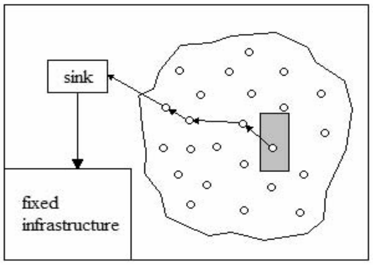

Figure 1: *Multi-hop routing from the area of interest (shaded rectangle) to the sink in a sensors field*

$k \approx 2$. As a result multi-hop forwarding is preferred over direct transmission (like traditional MANETs). Therefore data is routed back to the sink through a series of links between neighbouring nodes that may have no knowledge of the future or even current topology of the network due to its vast number of nodes and their high mobility.

A WSN application may be *continuous, event-driven, demand-driven* or *hybrid*. In the first case, data that are collected by the sensors, flow continuously towards the sink. In an event-driven application, data are collected and sent to the sink when an event of interest occurs. In the case of a demand-driven application, data are sent as a response to an explicit request that is pushed into the network in the form of a query. Finally a hybrid model can combine any of the above methods. At this point, the routing protocol design is inevitably linked to the application level. A simplified overview of a sensor field is provided in Figure 1, in which one can see the sink, area of interest and multi-hop data dissemination.

Furthermore, a routing protocol must take into consideration that the application's nature is not end-to-end, in contrast with most MANET applications. For example a number of nodes may be able to gather information from the area of interest. In the case of a demand-driven application this means that more than one node must receive the query. The challenge in this case is that flooding the network with the query messages results in unwanted energy waste, and therefore it should not be considered as a solution. Instead there should be a way to target the request to specific nodes that could have the potential to return relevant information. To this end, location-aided routing i.e. directing the packets appropriately, using exact position or approximate location information, seems to be a feasible approach. This is because such algorithms tend to choose the shortest path to the destination and avoid flooding, which results in low control packet overhead and energy savings.

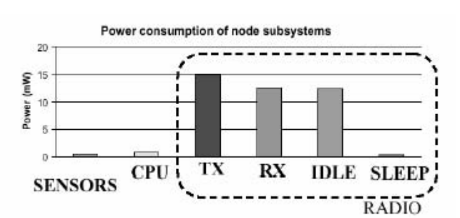

Figure 2: *Energy consumption during sensing, processing and executing the various communication operations as reported in [5]*

Probably the most critical design consideration of such an application is how processing is distributed over the WSN. As transmitting 1 bit of data proves to be much more expensive than processing it [6] (see figure 2), computation should be pushed inside the network in order to minimise transmissions. The question that arises is how this is possible and what does processing refer to when discussing sensor networks. First, it would be possible that a receiving node could send raw data to the sink, leaving the processing and analysis of the data to the fixed infrastructure. Instead, processing the signals on-board and responding in only with relevant to the query information is much more efficient as it saves energy from transmitting uninteresting data. In this case, sensor nodes are required to run signal-processing algorithms in order to recognise event and source types. This in fact has little to do with information routing. However data concerning a single event that are sensed by multiple nodes could be aggregated inside the network so that the information that will be finally routed back to the sink will be more accurate and the number of transmissions will be decreased. A WSN routing protocol should consider the data aggregation capabilities of the nodes.

3. Routing Protocols for Traditional MANETs

This section briefly reviews the main routing algorithms that have been proposed for traditional MANETs in order to clarify why they are not appropriate for WSNs.

3.1 Table-Driven Routing

Table-driven routing is also called *proactive* and *precomputed* routing. Algorithms that fall into this category are Destination-Sequenced Distance-Vector Routing (DSDV) [7], Clusterhead Gateway Switch Routing (CGSR) [8] and Wireless Routing Protocol (WRP) [9]. They all store routing tables at every node, recording the paths to all other nodes of the network and use periodic broadcasts to keep routing information up to date.

These protocols are not applicable to WSNs for a number of reasons. The most important is that they generate a great number of routing messages traffic in order to keep all nodes informed of all possible routes to all possible destinations. This traffic is generally too heavy for energy-limited motes. Considering in addition the high mobility and large scale of the WSNs, it is possible that, even if the energy restrictions were neglected, the paths to the distant motes would almost never be valid as they would change very fast.

3.2 On-Demand Routing

On-demand or otherwise *reactive* routing does not maintain routing information for all possible destinations at all nodes. Instead, it performs a *route discovery* procedure only when the source needs to send a message to a destination. The main representatives of this class are Dynamic Source Routing (DSR) [10], Ad-hoc On-Demand Distance Vector Routing (AODV) [11], Temporally Ordered Routing Algorithm (TORA) [12], Associativity Based Routing (ABR) [13] and Signal Stability-Based Adaptive Routing (SSA) [14]. Although on-demand routing protocols are a better approach to WSN routing optimisation because the routing traffic they create is much lighter and the storage space they require considerably smaller, they still suffer important disadvantages. For example, DSR assumes networks, which are small in diameter and have moderate mobility. A first observation is that the inherent route request phase inevitably enforces a delay in the actual packet transmission. In addition, in a highly mobile environment where links are established and disabled rapidly, messages may be lost on their way to the destination. Finally the dynamic nature of WSNs can locally create heavy traffic of bursty nature resulting in waste of energy and bandwidth.

4. Routing Protocols for WSNs

In response to the new design needs imposed, a new class of protocols, developed specifically for WSNs has appeared. The main representatives are Directed Diffusion [15], Low-Energy

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Adaptive Cluster Hierarchy (LEACH) [16] and Sensor Protocols for Information via Negotiation (SPIN) [17].

4.1 Directed Diffusion

Directed Diffusion is certainly one of the most interesting protocols. Data is defined as pairs of attributes and values. A query is expressed by the sink as four such pairs: the type of the event of interest (e.g. detection of a human), the rate at which the sink requests to receive data (e.g. every 100ms), the duration of time which the sink will be interested in listening for data (e.g. 10s) and the area of interest in which the target event happens (e.g. a rectangle of specified GPS coordinates). Such a query message is named an *interest*.

The sink initiates the protocol by flooding the network with periodic broadcasts of an interest with a high interval value, i.e. requesting data at low rate. An *interest cache* is maintained on each mote. The cache stores the received interest itself, a timestamp, the duration and several *gradients* up to the number of the neighbours. The gradients point to the neighbour from which the interest is received and the interval value requested. Upon receiving an interest, a node updates its interest cache and decides on whether to forward it to its neighbours based on if it has seen the same interest recently.

The Directed Diffusion protocol is data-centric and highly adaptive as it selects empirically low delay paths based on local interactions. This also implies that the non-end-to-end approach is adopted and that there is no need for global IDs throughout the network. Simulations comparing the protocol to flooding and omniscient multicast on the basis of the *average dissipated energy* and *average delay* metrics showed substantial improvements. However, while mobility is indirectly addressed by the second metric, scalability remains an issue in that performance simulations involved up to 250 nodes only.

4.2 Low-Energy Adaptive Cluster Hierarchy (LEACH)

LEACH organises the network into clusters. Each node decides on whether to become a clusterhead according to a certain probability that is specified a priori. Clusterheads process tasks requiring higher energy. LEACH addresses this by adopting a mechanism of changing clusterheads after specified intervals of time in order to spread battery usage fairly over the network. After clusterheads are elected, nodes select the cluster in which to affiliate by choosing the clusterhead with which they need the minimum energy to communicate.

LEACH differs from the rest of the protocols described here as it adopts direct instead of multi-hop transmission. However, its weaknesses are quite obvious. The authors have made a number of assumptions, which do not match typical WSN architectures and requirements. For example they show in some cases that direct transmission becomes more efficient than multi-hop. Adopting their idea and using its formalisation one can easily see that multi-hop routing is more efficient for a network of 10m diameter, consisting of just 10 nodes. Again there is no evidence that this protocol would scale for networks larger than 100 nodes and the authors neglect the fact that for larger diameters the base station may be out of the clusterheads transmission range. Furthermore the fact that the percentage of clusterheads must be determined a priori requires some knowledge of the network from beforehand, diminishing the self-adaptive property of the protocol.

4.3 Sensor Protocols for Information via Negotiation (SPIN)

SPIN is designed to address three deficiencies of flooding: *Implosion*, *overlap* and *resource blindness*. Implosion refers to the waste of resources taking place when a node forwards a message to a neighbour although the latter may have already received it from another source. Overlap occurs when two nodes sense the same region and produce and push into the network the same results. Resource blindness denotes the incapability of the protocol to adapt the node's behaviour according to its power status.

There are two versions of the protocol. SPIN-1 is a simple 3-stage handshake protocol. A node advertises its data (DATA) by broadcasting meta-data (ADV), which may include node-ID. A receiving node that has not seen the descriptive advertisement before, sends back a request (REQ) and then the sending node replies with the DATA. SPIN-2 simply incorporates an energy threshold below which a node will not participate in the handshaking. This way SPIN-2 implements negotiation and resource adaptation.

SPIN was tested on a 25-node testbed inside a rectangle of $40x40m^2$ therefore scale and mobility performance cannot be ascertained.

5. Location-Aided Routing

In this section we briefly present the basics of location-aided or position-based routing through methods proposed for traditional MANETs. We identify and distinguish between the following general categories: Greedy forwarding, Greedy routing with guaranteed delivery, Hierarchical routing and Geocasting and restricted flooding.

5.1 Greedy Forwarding

This first category includes algorithms to select the next neighbour to which the message will be forwarded among all in-range nodes. They can be considered to belong to the MAC layer and they are based on a local criterion assuming though that the destination position is known. These methods could be used when a WSN protocol needs to make local decisions.

Most Forward within Radius (MFR) [18] forwards the packet to the node that is closer to the destination in an attempt to minimise the number of hops. MFR assumes fixed range which results in deficiencies when a node is able to adjust its transmission radius. In the latter case Nearest with Forward Progress (NFP) [19] could be a better solution as it selects the nearest neighbour which is closer to the destination. Random Progress Method (RPM) [20] routes the message with equal probability towards a neighbour that enables forward progress. Further, Compass Routing selects the neighbour which is closer to the direction of the final destination. Finally in Geographic Distance Routing (GEDIR) [21], forwarding is similar to MFR with the addition of a termination criterion which applies when the neighbour selected is the one from which the message was forwarded. Intermediate Node Forwarding (INF) [22] is proposed as part of Grid routing (discussed later).

5.2 Greedy Routing with Guaranteed Delivery

The main problem inherent to the methods discussed in the previous paragraph is that the message is not guaranteed to be delivered to the final destination as the local nature of the forwarding decision may lead to a dead-end path. A way to overcome this problem is to forward the message to the

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neighbour with the smallest negative progress when no node with positive progress exists but this may induce loops into the path.

Face, Greedy-Face-Greedy (GFG) [23] and the Greedy Perimeter Stateless Routing (GPSR) [24] use planar graph traversal to overcome the dead-end problem. They construct a planar graph and route the messages on faces that are progressively closer to the destination by using the right-hand rule. This scheme guarantees delivery if there is a path in the original graph. GFG and GPSR exploit the planar graph traversal only when the message encounters a dead-end by switching from the "greedy" to the "face" or "perimeter" mode.

To enable routing decisions locally, additional information is included in the message such as the location where it switched to the perimeter mode, the point at which it entered the current face, the first edge it traversed on current face, the packet mode itself etc. Of course this is an overhead to be considered when discussing WSNs.

5.3 Hierarchical Routing

Hierarchical routing organises the network into some hierarchy in order to decrease its complexity and increase scalability and mobility. The most important representatives of this class are the Scalable Location Update-based Routing Protocol (SLURP) [25], Terminode [26,27,28] and Grid [22,29] routing.

All these protocols incorporate a distributed location service that disseminate location information across multiple nodes that form a hierarchy. SLURP uses k square subregions, Terminode exploits Virtual Home Regions (VHR) defined by a position and a radius and Grid Location Service (GLS) forms a hierarchy of squares so that order-n squares contain exactly four order-(n-1) squares. In order for a source to send a message to a destination, it first queries a location server node that belongs to the hierarchy about the destination's position.

Another common characteristic is that long distance routing is achieved using some greedy approach and when the message reaches the destination region it is sent to the specified node using one of the on-demand or table-driven protocols discussed earlier. In this context SLURP exploits MFR and DSR, Terminode uses Anchored Path Geodesic Packet Forwarding (AGPF) towards a destination which is defined using a Location Dependent Address (LDA) and Grid combines geographic forwarding [33] with a modified version of DSDV.

While these design choices constitute the protocols that are very scalable, their implementations do not match the lightweight protocol requirement imposed by WSNs' energy and storage limitations. SLURP for example uses at least nine different control packets and maintains four data structures on each node.

5.4 Geocasting and Restricted Flooding

Geocasting is deployed to deliver messages to all nodes inside a specified area. Among other techniques, restricted or partial flooding can be used for this. Restricted flooding isolates and floods only a part of the whole network towards the destination area. The most important protocols that fall in this category are the Location-Based Multicast (LBM) [30], which is an extension of Location-Aided Routing (LAR) [32] and Distance Routing Effect Algorithm for Mobility (DREAM) [31].

- **LAR** exploits restricted flooding to perform unicasting. Assuming that the source knows the destination's position x_0 at time t_0 and it has an estimation of its speed u (e.g. the average or maximum speed among the mobile nodes), it initiates a route request at $t_1 > t_0$. The *expected zone* i.e. the zone in which the destination node is expected to be, is defined as the circle of radius $u(t_1-t_0)$, centred at x_0. In LAR-1 the *request zone* is set to be the smallest rectangular, which includes the source node and the expected zone. The source initiates the route request by sending a message that contains the coordinates of the rectangular. The nodes that are inside the request zone place their IDs in the message and forward it. The ones outside the zone discard it. When the destination receives the request, it replies with a message containing its location, a timestamp and the route. The reply is routed by reversing the path inside the request just like in DSR. In LAR-2 the request zone is defined implicitly. An intermediate node that receives the request, forwards it only if its distance from the destination is smaller than the one of its predecessor from the destination. To achieve this, nodes forward their locations together with the request. **LBM** extends LAR to perform geocasting in the obvious way.
- In **DREAM** each node transmits control packets periodically. The frequency of these transmissions is proportional to its speed so as to optimise each rate according to the individual mobility. The concept of the *distance effect* is also introduced. According to this, a *life time* is associated with each control message in order to model the fact that two mobiles that are far apart see each other moving slower than if they were closer, causing the message to be discarded after a specified number of hops. The majority of the messages are *short lived* while other *long lived* ones are sent rarely and traverse the whole network. Assuming an average speed u (or even a speed probability function) for the nodes and knowledge of a destination's position x_0 at time t_0, the source can route a message at time t_1 towards the disk with radius $u(t_1-t_0)$ centred at x_0. Each node forwards the message only to the neighbours that lie inside the area bounded by the disk and its two tangents that cross at the point where the source lies at t_1.

6. Conclusion

In this paper we have identified the design requirements for an efficient routing protocol for WSNs as imposed by the motes' energy and storage restrictions. We have also presented a survey and classification of existing algorithms proposed for routing over MANETS with and without position-awareness, routing over WSNs and broadcasting using the least possible energy, summarising the most interesting characteristics of each of the protocols and commenting on their applicability on WSNs.

We conclude that the existing protocols address selectively specific requirements and match only some of the design aims we have distinguished. There is certainly not a protocol that supports mobility, scalability, data aggregation and serves energy efficiency and fault tolerance at the same time.

We believe that location awareness is the only difference between traditional MANETs and WSNs that can actually be used for optimisation reasons. There is certainly a trade-off between scalability, mobility and location-awareness in the sense that as the networks' size and mobility increases, the location information bulk becomes larger and the necessary updates more frequent. In this context, an adaptive lightweight location service supporting routing over a hierarchy that enforces balanced energy conservation across the whole network to ensure prolonged lifetime is needed and would be considered as a breakthrough development in this research area.

Acknowledgements

We would like to thank Naranker Dulay for his kind suggestions.

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