Location aware sensor routing (LASeR) protocol for mobile wireless sensor networks

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Location Aware Sensor Routing (LASeR) Protocol for Mobile Wireless Sensor Networks

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Abstract— Location Aware Sensor Routing (LASeR) protocol is a novel solution to the challenges of routing in mobile wireless sensor networks (MWSNs). It addresses the high reliability and low latency requirements of emerging applications. The protocol uses location information to maintain a gradient field even in highly mobile environments, whilst reducing the routing overhead. This allows the protocol to utilise a blind forwarding technique to propagate packets towards the sink. The protocol inherently utilises multiple paths simultaneously to create route diversity and increase its robustness. LASeR is designed for use in a high variety of MWSN applications with autonomous land, sea or air vehicles. Analytical expressions are derived and evaluated against the simulations. Extensive modelling and simulation of the proposed routing protocol has shown it to be highly adaptable and robust. It's compared with the recent MWSN PHASeR protocol, the high performance MACRO protocol, as well as AODV and OLSR. Protocols are evaluated on packet delivery ratio, end-to-end delay, overhead, throughput and energy consumption. The results highlight both the high performance of LASeR in various challenging environments and its superiority over the state-of-the-art.

I. Introduction

The topic of wireless sensor networks (WSNs) has recently gained a lot of research interest due to the availability of low cost, low power transmitters, making it cost effective to create small networks of sensors [1]. These sensors are typically radio enabled nodes with simple transducers connected to a microcontroller. Of primary importance in all WSN applications is the routing protocol, which defines how data is passed from the sensors to the sink. The majority of WSN applications do not require the routing protocol to take into account the movement of nodes because the nodes are static or just very slow moving. Introducing mobility to the nodes can cause frequent changes in topology. This dynamic topology in mobile wireless sensor networks (MWSNs) causes problems for routing protocols, since there is no fixed path from source to sink. Mobile ad-hoc networks (MANETs) also share this problem; however their requirements differ to those of a MWSN. As such, the problem of routing in a MWSN will necessitate an alternative solution to those protocols designed for static WSNs or MANETs.

There are a multitude of applications for MWSNs, including wildlife monitoring [2], surveillance [3] or monitoring air contamination [4]. In applications such as these, the advantages of using mobile nodes are in allowing the whole network to move with a target, the ease of redeployment and in the increased area they can cover [5]. The motivation for this work is in this rapidly growing number of applications, which will all require individually tailored solutions. As such, although this work is applicable for many applications, design choices will be based on the target application of terrain mapping, in which a small number of autonomous drones are deployed to gather topographical information. This data can then be transmitted back to the sink, where an image may be built up. The terrain may be terrestrial, extraterrestrial or aquatic, based on the requirements of the user.

Location Aware Sensor Routing (LASeR) protocol is a novel geographic routing protocol, which uses location information to facilitate a method of gradient routing in mobile environments. LASeR uses blind forwarding to propagate data through the network, which inherently creates route diversity [6]. So, if one of the routes was to fail, there would be another available to deliver the packet.

The next section gives an overview of the current literature regarding the positioning of this work, followed by a description of the proposed protocols design and functionality. Then analytical expressions are derived before the simulation results are presented and the paper is concluded.

II. Related Work

In general MWSN routing protocols take influence from two main research areas; WSNs and MANETs. WSNs are commonly considered to be static and so cannot handle the mobility of nodes, whereas MANETs are designed to cope with mobile nodes. Contrastingly to MANETs, most sensor networks only require data to flow in one direction; from source to sink. In addition to this the hardware and power constraints on these small sensor nodes, means that protocols must have low computational complexity and low energy consumption. Energy is a major concern with battery powered mobility platforms since high energy consumption can dramatically reduce the lifetime of the network.

MANET protocols are often defined as proactive or reactive. The proactive protocols, such as OLSR (Optimised Link State Routing) [7], attempt to ensure that each node has an active path to every other node. This usually requires the flooding of topology data, which can cause huge amounts of congestion in large networks. Contrastingly, reactive protocols, such as AODV (Ad-hoc On-demand Distance Vector) [8], only discovers routes when they are needed. This can often reduce the overhead of control packets, making reactive protocols a more common choice for mobile networks.

This can be seen by the number of reactive protocols that have been adapted from MANETs to MWSNs. For example, AODV-PSR (AODV with Preemptive Self Repair) [9], is an adaptations of AODV designed for MWSNs, which, attempts to predict link breaks and find replacements. Another technique used is opportunistic routing, such as seen in GOR (Geographically Opportunistic Routing) [10], which splits up the network into sections. Using location information, each node then tries to forward the packet to a node in a section that is closer to the sink. It opportunistically attempts to transmit to the furthest section within its transmission radius, before trying increasingly closer sections.

Alternatively, WSN routing protocols are categorised by their structure, as either flat or hierarchical. The hierarchical protocols, like LEACH (Low-Energy Adaptive Clustering Hierarchy) [11], split the network up into clusters. Sensor nodes then forward data to a cluster head, which then forwards it to the sink. This approach has been shown to reduce energy consumption in static sensor networks. However, the requirement of nodes to firstly elect and then associate themselves with a cluster head can cause significant overhead, especially if nodes are frequently moving between different clusters.

Adaptations for MWSNs include LEACH-M (LEACH-Mobile) [12] and LEACH-ME (Low-Energy Adaptive Clustering Hierarchy – Mobile Enhanced) [13], which allow nodes to dynamically switch between clusters. This enables the protocol to adapt to changing topologies by providing a method of determining when a node is disconnected and should then join another cluster. In LEACH-ME, networks are made more stable by choosing the least mobile nodes to be cluster heads.

MBC (Mobility Based Clustering) [14], works in a similar way to LEACH-M except that it utilises a more complex method of cluster head election, which takes into account estimated connection time, residual energy, the cluster heads node degree and distance. These measures are used to generate a suitability metric, which allows nodes to make an informed choice about which cluster head to associate with. Another approach is presented in [15], which describes a protocol that is able to control the location of the mobile node in order to maximise the coverage of the sensors over the network area. In this way, it attempts to prolong the lifetime of the networks by maintaining low energy routes as an additional objective. ZBR (Zone Based Routing) [16] uses location awareness to define clusters. In this way each node will know which cluster it's in by its current location. Cluster heads are determined by each node broadcasting a mobility factor, such that the least mobile node can be appointed.

Contrastingly, flat protocols, such as Directed Diffusion (DD) [17], require no infrastructure, which makes them the preferred choice in mobile networks. Since they are not designed for mobile networks, DCBM (Data Centric Braided Multipath) [18] was adapted from DD to be used in MWSNs. DCBM lets the sink flood the network with a query, the path of which is recorded by the intermediate nodes. Once a node with the requested information receives the query it may respond along multiple paths towards the sink. In [19], a state-of-the-art cross-layer protocol is proposed for MWSNs. MACRO (Mobility Adaptive Cross-layer Routing) is a recent routing solution that shares RSSI and speed information between layers.

It saves energy by utilising a MAC layer with an adaptive duty cycle. It also uses link quality information to ensure the route reliability. At this point it should also be noted that many delay tolerant networks are also considered to be MWSNs [20], however the sparsity of the nodes require a different approach to the routing, and, as such, will not be considered here.

The literature suggests that the most suitable protocols for mobile networks are those with the least overhead, which makes gradient routing a particularly applicable technique. The static WSN protocol, GBR (Gradient Based Routing) [21], floods the network to set up a hop-count gradient metric at each node. Then nodes share their gradients with their neighbours, so that when a node wishes to transmit, it can select the neighbour closest to the sink as the next hop. Unfortunately, in a MWSN the changing topology would require the network to be flooded periodically in order to maintain the gradient, which would cause significant network congestion. One recent gradient routing protocol is PHASeR (Proactive Highly Ambulatory Sensor Routing) [22], which targets MWSNs. The protocol also maintains a hop count through the sharing of local topology information, which can sometimes mean that the gradient is out-of-date. Additionally, PHASeR utilises packet encapsulation, which allows it to transmit the data from more than one source in a single packet. However, this creates large packets and can cause long delays.

Of primary relevance to the presented work is the location aware protocol GPSR (Greedy Perimeter Stateless Routing) [23], which works in a similar way to GBR. The main difference is that the gradient is derived from location information in order to avoid flooding, as is also the case with LASeR. However, LASeR uses a method of blind forwarding as opposed to selecting a single next-hop node. In blind forwarding, a transmitting node broadcasts its packet to all of its neighbours; the neighbours then use the received gradient to determine whether they should forward the packet. This technique can be seen as far back as 1991 [24] and has been used on multiple occasions for static WSNs [25, 26]. The main issue with using blind forwarding in mobile networks is maintaining an up-to-date gradient. Since, in LASeR, this is done using location information, the need to flood the network is negated making it an ideal solution for MWSNs.

The use of location awareness also produces the issue of the dead-end problem [23], in which a node is locally maximal and as such has no neighbours that are closer to the sink, which prevents the progress of any data received by this node. This is addressed in GPSR with the use of the right-hand rule. The PAGER (Partial-Partition Avoiding Geographic Routing) [27] algorithm was proposed as an alternative solution to the dead-end problem in GPSR. In comparison, LASeRs use of blind forwarding causes a single packet to take multiple paths through the network, which mostly alleviates the dead-end problem. As such the contribution of this work is in a novel routing protocol designed for MWSNs, which utilises available location information to route packets towards the sink. The protocol also takes advantage of the blind forwarding technique to create a unique protocol, which requires very little control overhead, making it suitable for highly dynamic networks.

III. PROTOCOL DESCRIPTION

The application of terrain mapping requires nodes to autonomously gather topographical information and report this to the sink. The data will need to be accompanied by some form of location information so that it can be mapped. This means that the nodes will be equipped with some method of localisation. This may be in the form of GPS [28], although the addition of GPS for every node requires significant cost and power. However, the DRLMSN (Dead Reckoning Localisation for Mobile Sensor Networks) technique proposed in [29] provides a localisation solution, which does not require all nodes to be equipped with a GPS module, yet still allows the nodes to move freely.

LASeR takes advantage of the available location information in order to route packets. Additionally, it is likely that the nodes will be deployed to map an area for a certain time period. This means that as long as each node has enough power to last for the duration of the mission, the number of nodes will remain fixed. The traffic rate will also be relatively periodic as nodes will generate data based on a given resolution. The packet structure used is shown in table 1, in which n is the total number of sensor nodes, L is the length of one side of the square network area and Q_L is the quantisation level in meters. L_{data} is the number of data bits required by the application and the total packet length is given as L_p.

Field name	Node ID	Location	Data	Priority bit	Packet ID
Size (bits)	$\lceil \log_2 n \rceil$	$\left\lceil \log_2 \left(\frac{\sqrt{2} \cdot L}{Q_L} \right) \right\rceil$	L_{data}	1	$\lceil \log_2 n \rceil$
Total size (bits)	$L_P = 2 \cdot \lceil \log_2 n \rceil + \left\lceil \log_2 \left(\frac{\sqrt{2} \cdot L}{Q_L} \right) \right\rceil + L_{data} + 1$				

Table. 1. LASeR packet structure showing the five fields and their respective sizes. The expression for the total packet size, L_P, is also given, where $\lceil \cdot \rceil$ indicates the ceiling function.

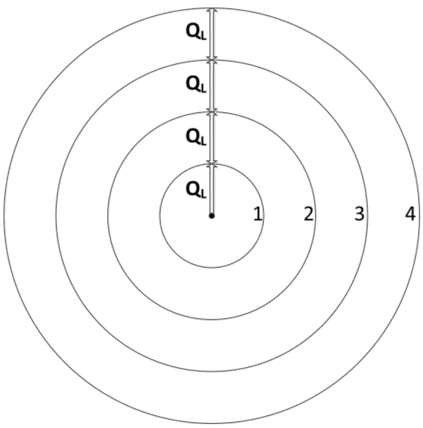


Fig. 1. Conceptual radial bands emanating from the sink, showing location index. The indexes are used by nodes as the gradient metric, which indicates the direction that packets should be sent.

A. Gradient Metric

The location information can be from any available geographic positioning technique, which may be application specific. Though it should be noted that some of these techniques require significant energy cost and their accuracy can be unreliable.

For the purposes of this paper the location information is assumed to be perfect. This is to isolate the routing protocol such that its performance may be analysed without the added effects of an imperfect localisation technique.

Each node's distance from the sink is quantised, such that an integer value can be used as a gradient. Conceptually, this creates radial bands emanating from the sink as shown in figure 1. A node's location corresponds to the location index of the radial band that it is in. For example if the quantisation level, Q_L, is 5 meters and a nodes Euclidean distance from the sink is 12 meters, this would put it in the third radial band. Accordingly, the node would be assigned a location index of 3. These location indexes are the metrics used to create the gradient field. In terms of the field size, using a 40 meter by 40 meter network as an example, the furthest possible distance a node may be from the sink is 56.57 meters. By splitting this length up into increments of 5 meters, 12 segments are created. In order to store these 12 location index values, 4 bits are needed in the packet, which is corroborated by the location field size equation in table 1.

B. Forwarding Data

LASeR uses blind forwarding to transmit packets, which means that the decision to forward a packet is made by the receiving node, rather than the transmitting node. So, when a node receives a packet it stores it in a queue until its next opportunity to transmit. Then the node will decide if any of the packets in the queue should be forwarded. If so, it will blindly transmit the packet to all of its one-hop neighbours, otherwise it will drop the packet.

The decision to forward a message is made based on the received packets gradient metric. In this way, there are three possible actions to take based on a received packets' location information:

- If the location information indicates that the packet has come from a node that's further away from the sink, then it should be forwarded.
- If the packet has come from a node that is the same distance away from the sink, then it should be forwarded, with the priority bit clear, which will be discussed in the next subsection.
- If the packet has come from a node that's closer to the sink, then it should be dropped.

Overall, the location information is used as a gradient metric, which originates at the sink, as such, packets should be forwarded down the gradient. When the packets are forwarded they are updated with the current location index of the transmitting node. In this way, the receiving node will know from which direction the packet is coming and act accordingly. Since the choice to forward a packet is made by the receiving node, it is likely that multiple neighbours will decide to pass on the message, which subsequently creates route diversity. This route diversity will aid the protocols ability to deliver packets in a changing environment regardless of whether the topology is changing from the movement of nodes or the degradation of links in a fading channel. This will increase the redundancy of packets, which improves the reliability of the protocol as packets are more likely to be successfully delivered. However, this added overhead will also mean that congestion may become an issue with high traffic levels. Subsequently, nodes are only allowed to transmit a packet once, which limits the amount of redundancy introduced into the network and enables LASeR to handle higher traffic levels. Additionally, it should be noted that because LASeR does not use a routing table or path discovery techniques, if a node fails the protocol will simply continue to run and naturally adapt to the new state of the network, making LASeR very robust.

C. Packet Priority

Packets with the priority bit set are designated as priority packets, whereas packets with the priority bit cleared are designated as diversity packets. A diversity packet is one that has been forwarded by a node with the same location index as the one that transmitted it. For example, a node with a location index of 3 broadcasts a priority packet to its neighbours. The neighbours with a location index of 2, store the packet for forwarding and the neighbours with a location index of 4 simply drop the packet. The neighbours that also have a location index of 3 clear the priority bit and store the packet for forwarding. The use of the priority bit increases the route diversity of the protocol and also helps to alleviate the dead-end problem.

D. General Operation

The operation of each sensor node can be summarised by the flow chart in figure 2, which shows how the protocol initially determines whether it should be transmitting or listening to the medium. This is based on information passed up from the MAC layer. It then either queues any data it hears from other nodes or selects a packet to forward. Packet selection is done on a first come first serve basis, where priority packets are always given precedence over diversity packets. In other words, the oldest packet with the highest priority is always transmitted first.

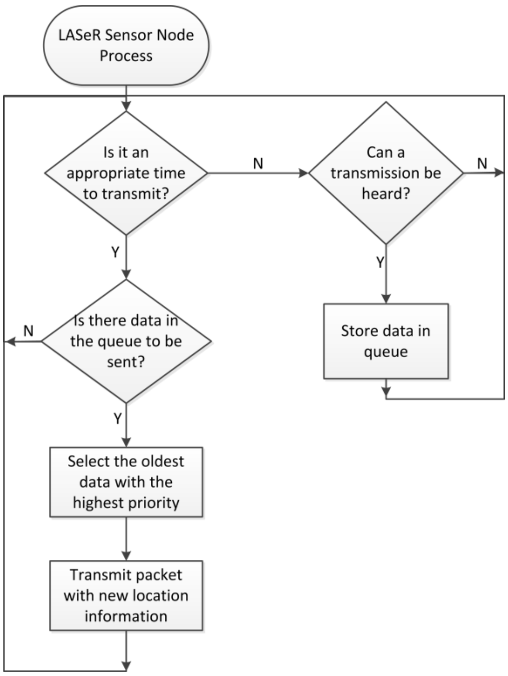


Fig. 2. Flow chart of the operation of a sensor node in LASeR.

E. MAC Layer

The choice of MAC layer is an important aspect of this protocol; since LASeR uses blind forwarding it is likely that multiple neighbours will hear a node's broadcast and decide to forward the packet. This can cause significant MAC layer problems, especially when considering the hidden node problem. One of the most popular MAC layers is the 802.11 DCF MAC [30], which uses the technique of carrier sense multiple access (CSMA) with collision avoidance (CA). This technique requires a node to first listen to the channel; if it's clear then the packet can be sent, else it should wait for a random amount of time before trying again. Using CSMA/CA in LASeR, a node may transmit to all of its neighbours, then each of them will listen to the medium. At this point it's likely that more than one of the neighbours will sense the channel to be free and try to transmit, causing collisions. Additionally, the 802.11 DCF MAC also defines the use of acknowledgements (ACKs) and a request to send (RTS), clear to send (CTS) handshake. In LASeR, since multiple nodes receive the data, more than one node may respond with an ACK. These ACKs are likely to collide and potentially cause the unnecessary retransmission of a packet. A similar problem occurs with the handshake. This suggests that LASeR would be better served with a collision free MAC layer rather than a contention based one.

Since the target application is likely to use a fixed number of nodes for each mission, this work utilises a global time division multiple access (TDMA) scheme. This MAC allocates each node a time slot, which is sized to allow for the transmission of a single packet. The time slots loop cyclically, allowing each node to take it in turns to transmit contention free. The MAC can be adjusted for the specific number of nodes in the mission before deployment. Though it's not the scope of this work, long deployments will require some kind of synchronisation, for which there are a number of techniques surveyed in [31]. Additionally, [32] describes a working implementation of a TDMA based sensor network, which uses an out of band AM transmitter to maintain global synchronisation. Alternatively, if the location information is acquired via a satellite based system, each node may also synchronise its clock to the received time from the satellites [33].

IV. Mathematical Analysis

This work focuses on five metrics; average end-to-end delay, packet delivery ratio, throughput, overhead and energy consumption. Analytical expressions are derived for each metric in order to characterise the protocols performance. The expressions are based on using the global TDMA MAC layer.

A. Average End-to-End Delay

The average end-to-end delay, D_{av}, is defined as the average time between a node creating a packet and it being received at the sink. Given as:

$$D_{av} = h \cdot T_q. \qquad (1)$$

where h is the number of hops and T_q is the delay at each node.

The average hop-count between the source and the sink is taken from [34]:

$$h = \frac{d_{av}}{d_{hop}} = \frac{2 \cdot L}{3 \cdot r \cdot cos\left(\frac{\pi}{2 \cdot N_n}\right)} \tag{2}$$

where d_{av} is the average Euclidean distance between the source and destination, and d_{hop} is the average distance of a single hop. L is the length of the square network area, r is the node's transmission radius and N_n is the expected number of neighbours to each node. N_n is given by

$$N_n = \left(\frac{\pi \cdot r^2}{L^2}\right) \cdot (n-1). \tag{3}$$

where n is the total number of nodes in the network.

The arrival rate of packets to a node, λ, is assumed to follow a Poisson distribution and each node is considered to be a single server. Since the global TDMA has a deterministic medium access time, the service time, T_s, is constant. For this reason each node is modelled as an M/D/1 first come first serve (FCFS) queue. In each node packets are created at a rate of f_p. The total number of packets forwarded by a node is equal to the packet creation rate multiplied by the number of nodes, whose data it forwards:

$$\lambda = \frac{f_p \cdot (n-1)}{N_n^2} \tag{4}$$

As each node gets the chance to transmit once in a TDMA cycle, the service time is simply

$$T_s = \varDelta \cdot (n-1) \tag{5}$$

where $\varDelta$ is the length of a single time slot, which is given by:

$$\varDelta = \frac{L_p}{R_b} + \frac{r}{c} \tag{6}$$

where R_b is the bit rate and c is the propagation velocity of the signal.

Using the Pollaczek-Khinchin formula for the mean time in the system, T_q, the delay can be described as:

$$D_{av} = \frac{h \cdot T_s \cdot (2 - \lambda T_s)}{2 \cdot (1 - \lambda T_s)}. \tag{7}$$

This expression highlights the contribution of the number of hops and packet arrival rate to the delay time.

B. Packet Delivery Ratio

The packet delivery ratio (PDR) is defined as the fraction of created packets that are successfully received by the sink: as:

$$PDR = \frac{P_{rx}}{P_{tx}}. \tag{8}$$

The TDMA MAC layer is contention free, so there will be no packet loss from collisions. It is also assumed that the network is well connected and as such nodes will not become disconnected. For this reason the main cause of packet loss will be through link breakages on the path of a packet.

Taking an expression for the average link lifetime, t_{av}, adapted from [35]:

$$t_{av} = \frac{d_{link}}{\vec{v}} = \frac{4 \cdot r}{\pi \cdot v_{max}} \tag{9}$$

where d_{link} is the link distance, $\vec{v}$ is the relative velocity between the transmitter and receiver and v_{max} is the maximum speed that a node is capable of. So, during the time between a packet is created and received at the sink, the probability of a link breaking, P_{break}, is

$$P_{break} = \frac{D_{av} \cdot \pi \cdot v_{max}}{4 \cdot r} \tag{10}$$

The expected number of broken links, L_{broken}, is given by:

$$L_{broken} = P_{break} \cdot \binom{n}{2} \cdot \left(\frac{\pi \cdot r^2}{L^2}\right) \tag{11}$$

where $\binom{n}{2}$ is the binomial coefficient of *"n choose 2"*. If it's assumed that a link break on the path of a packet causes packet loss, the packet loss ratio (PLR) is given as:

$$PLR = L_{broken} \cdot \frac{h}{\binom{n}{2} \cdot \left(\frac{\pi \cdot r^2}{L^2}\right)} \tag{12}$$

Given that PDR is

$$PDR = 1 - PLR. \tag{13}$$

The final PDR expression is

$$PDR = 1 - \left(\frac{D_{av} \cdot \pi \cdot v_{max} \cdot h}{4 \cdot r}\right). \tag{14}$$

This shows how the speed, delay, transmission radius and number of hops, affect the PDR.

C. Throughput

The throughput, TP, is defined here as the number of data bits successfully delivered to the sink, per second. This is expressed as

$$TP = \frac{L_{data} \cdot N_p \cdot PDR}{T_t} \quad (15)$$

where N_p is the total number of packets produced and T_t is the total deployment time of the network. The expression shows how the throughput is largely affected by the number of packets generated and the number of packets lost.

D. Overhead

Overhead, OH, is made up of two parts; control overhead and packet overhead. Control overhead is the fraction of bits in control packets over bits in data packets. Packet overhead is the fraction of bits in each sensor data packet that is not data.

Here, the total overhead is characterised by the total number of bits transmitted per successfully delivered data bit:

$$OH = \frac{B_{tx}}{L_{data} \cdot N_p \cdot PDR} \quad (16)$$

where B_{tx} is the total number of bits transmitted. B_{tx} is given by

$$B_{tx} = N_f \cdot N_p \cdot L_p \quad (17)$$

where N_f is the number of forwarding neighbours.

E. Energy Consumption

In this work, only the energy used to transmit and receive messages is considered. This is because the transceiver contributes the most to the power consumption in comparison to that of the processor. There are multiple other factors, which may make code more or less efficient and will affect the processors energy consumption. Other energy costs come from things like sensors, the mobility platform and location determination, which are hardware specific and difficult to account for.

The energy consumption, EC, is characterised in terms of joules used per second per node:

$$EC = \left(\frac{V_{batt}}{R_b}\right) \cdot \left(\frac{(I_{tx} \cdot B_{tx}) + (I_{rx} \cdot B_{rx})}{n \cdot T_t}\right) \quad (18)$$

where V_{batt} is the voltage of the batteries, I_{tx} and I_{rx} are the current consumptions of the transceiver when transmitting and receiving respectively and B_{rx} is the total number of bits received. B_{rx} is taken as

$$B_{rx} = B_{tx} \cdot N_n. \quad (19)$$

To evaluate these expressions, some knowledge of the hardware is required.

V. Modelling and Simulation Results

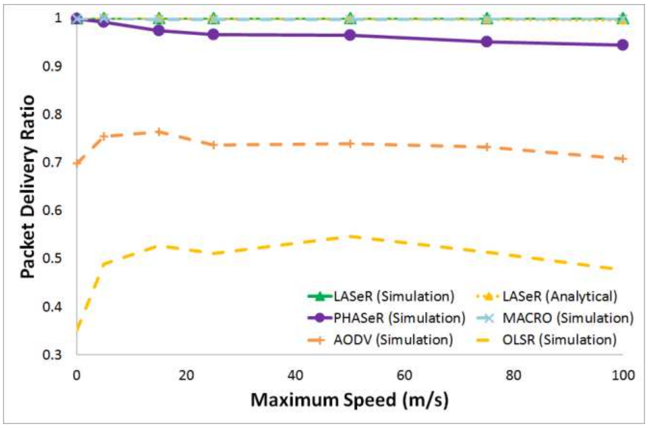
The simulations were performed in OPNET Modeler [36] and modelled to imitate the conditions of a terrain mapping application. Since, the deployment is likely to use a small number of mobile nodes, 25 nodes were used for the simulations. The area to be mapped will vary based on the specifics of the mission, so for the simulation 600m by 600m was used to represent a medium sized area. It maybe that the nodes are programmed to follow a set flight path, which would imply a static topology, however varying channel conditions may cause some links to drop out. For this reason a random waypoint mobility model is used with 0s pause time. The minimum speed is set to 0m/s and the maximum is 25m/s. This maximum is a reasonable average for a small unmanned craft based on land, in the air or underwater. In general these parameters should create a well-connected network that is not overcrowded. Also, the use of a constrained network area will reduce the likelihood of a node or a group of nodes becoming disconnected for long periods of time. To give an idea of the general network density, the metric $(n\pi r^2)/L^2$ from [1], with the above parameters, yields 13.6, which suggests a medium density network. To put this in context, a very sparse network of 20 nodes in a 2000m by 2000m network would give a value of 0.98, whereas a dense network of 150 nodes in a 500m by 500m networks would give a value of 117.8.

It is assumed that, within the transmission radius, nodes can communicate perfectly, so no errors are introduced from noise or fading effects. This will isolate the simulation results to the performance of the routing protocol, which will allow for closer analysis of LASeR. A packet generation rate of 1pk/s is used to give a reasonable resolution of the area. Each packet is generated with 32bits of data, which is sufficient to contain the node's position and some terrain information. The transmission radius and data rate are modelled on the Memsic IRIS motes [37] and set to 250m and 250kbps respectively.

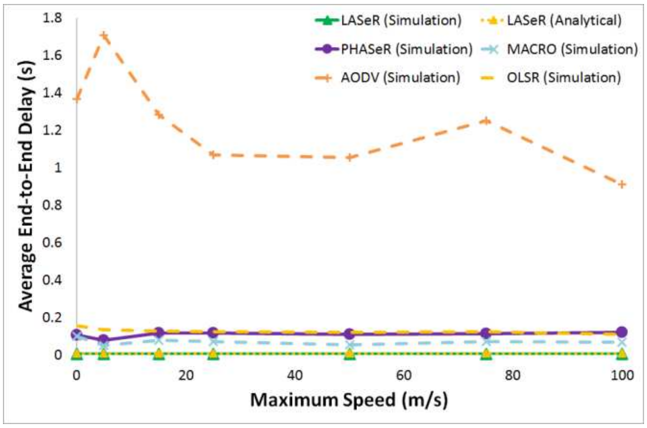
For comparative purposes, simulation results have also been gathered for PHASeR, MACRO, AODV and OLSR. PHASeR and MACRO represent the current state-of-the-art in MWSN routing protocols. AODV is the basis for the popular ZigBee standard, which is one of the most popular protocols for static WSNs. Since AODV is a reactive protocol, the proactive OLSR protocol has been included for balance. Results are shown for PDR, average end-to-end delay, overhead, throughput and average energy consumption. All of which are taken as defined in the previous section. It should be noted that although jitter results are not given here the fixed service time of the global TDMA MAC keeps the delay variance relatively stable in contrast to dynamic TDMA, in which the scheduling of nodes can cause strong jitters [38].

A. Mobility

The mobility results in figure 3 shows the protocols in the previously described scenario with a varying maximum speed of [0, 5, 15, 25, 50, 75, 100]m/s. The PDR shows LASeR and MACRO to be near perfect, with LASeR having an average improvement on MACRO by just over 0.16%. PHASeR shows a lesser performance, with more packets being lost as the mobility level increases. Additionally, the PDR of AODV and OLSR are considerably lower than the other three protocols, indicating a high level of packet loss. The analytical results show an accurate approximation to the simulated results as do the average end-to-end delay results. LASeR is also shown to have better delay than the other four protocols by over 96ms, with PHASeR, MACRO and OLSR having similar levels of latency and AODV giving the worse performance. In the same way, the throughput highlights LASeR as the best with the analytical expressions characterising this well. Also, PHASeR shows a slight improvement over MACRO in throughput, which is due to PHASeRs slightly lower delay. The overhead results show a clear distinction between the protocols, with LASeR, PHASeR and MACRO having a large improvement on AODV and OLSR. Generally, LASeR gives a noticeable improvement over all compared protocols, however PHASeR yields a marginally lower energy consumption than LASeR, which occurs from the reduced level of PDR. The analytical results show a good approximation for overhead, but slightly over estimates the energy consumption.



(a)



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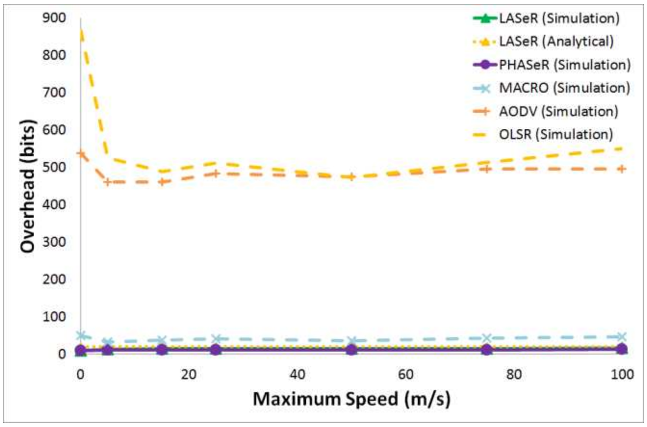
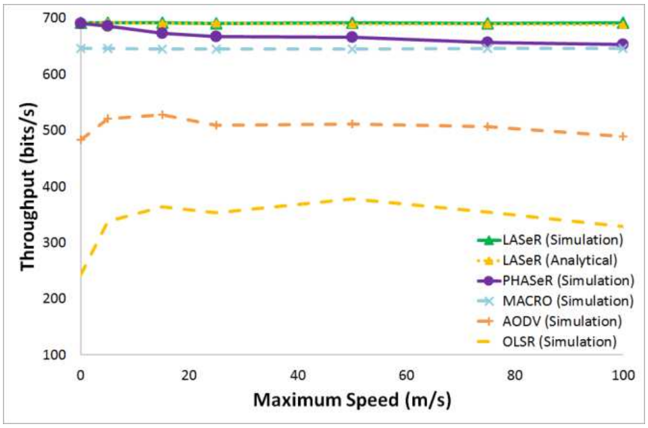


(c)



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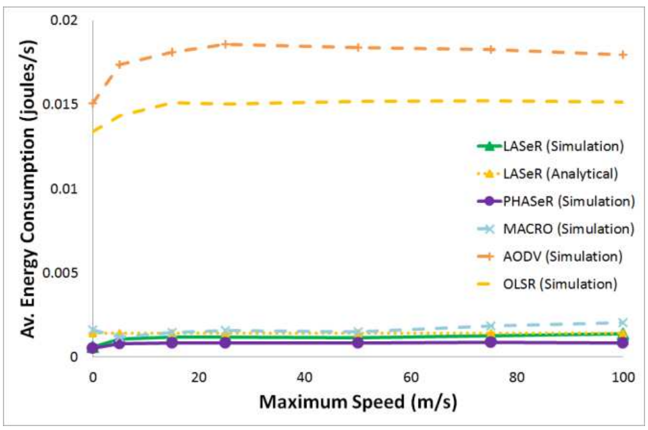


(e)

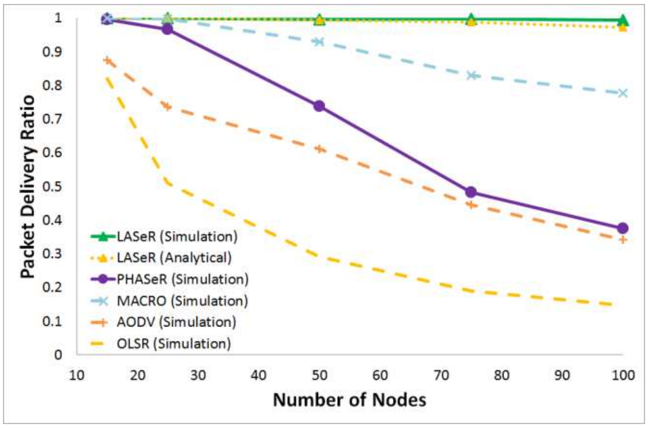
Fig. 3. Results for LASeR, PHASeR, MACRO, AODV and OLSR for varying maximum speeds: (a) PDR, (b) Average End-to-End Delay, (c) Overhead, (d) Throughput and (e) Average Energy Consumption.

B. Scalability

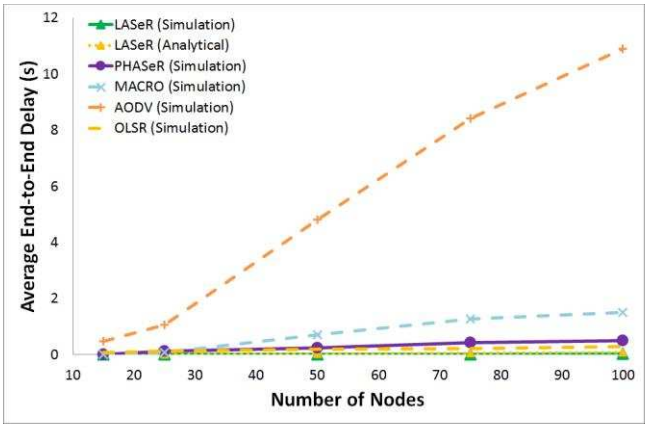
Figure 4 gives the simulation and analytical results for varying the number of nodes between [15, 25, 50, 75, 100]nodes. In order to maintain a reasonable ratio of nodes per square meter, the length of the square network is also varied to [400, 600, 1000, 1200, 1500]m accordingly. In terms of the density metric previously, this yields [18.4, 13.6, 9.8, 10.2, 8.7], which shows a relatively small changes in the overall scenario density. All other parameters are kept constant with a maximum speed of 25m/s and a packet generation rate of 1pk/s. The PDR of PHASeR, MACRO, AODV and OLSR show significant degradation as the number of nodes increases, whereas LASeR is consistently high. The analytical expression is good but slightly underestimates the PDR with high numbers of nodes. Whereas, in terms of end-to-end delay, it closely approximates the simulation over all scenarios. Similarly to LASeR, OLSRs delay remains low, though this is due to its high packet loss. Both PHASeR and MACRO show a slight delay increase towards high numbers of nodes, whereas AODV's latency increases significantly. In terms of overhead, the results show LASeR and PHASeR to be consistently low where the other three protocols have a significant increase as the number of nodes rises. Additionally, the analytical expression gives an accurate portrayal of the simulation in this case. Looking at the throughput results, all protocols show an increase in throughput, which is expected as adding more nodes creates more traffic. PHASeR, AODV and OLSR both show a shallow increase toward high numbers of nodes, whereas MACRO shows a much better level of throughput. LASeR is shown to have superior performance in throughput, over the entire range, with the analytical giving a close characterisation. The energy results show MACRO and LASeR to have comparable energy consumption at low numbers of nodes. However as the number of nodes increases MACRO becomes increasingly power hungry, whereas LASeRs energy consumption only shows a slight elevation. PHASeRs energy consumption is the lowest, but this comes at the cost of a significant number of lost packets. Overall, the analytical expression slightly under estimates LASeRs energy consumption.

C. Traffic

The results for varying packet generation rates are given in figure 5 for [0.1, 0.5, 1, 2.5, 5, 10]pk/s. LASeRs PDR remains near perfect for the varying traffic levels, which is corroborated by the analytical expression. PHASeRs PDR shows a slight increase to begin with and then remains relatively constant, although at a lower level than that of LASeR. MACRO shows a clear drop in PDR after the 5pk/s point, which is also highlighted in the delay results by a significant increase. LASeRs delay is consistently lower than all other protocols, however both PHASeR and MACRO show comparatively low delays at various points over the range. OLSR has a low delay due to its high packet loss, but still shows a large increase towards higher packet generation rates. The analytical results give a good approximation to the simulated LASeR. The change in MACRO is also clear in throughput, which seems to plateau after 5pk/s. This indicates an upper bound for MACRO in this scenario. PHASeR shows a good level of throughput over the entire range, but both the analytical and simulated results for LASeR show it to give better throughput than the other protocols, especially at higher packet generation rates. All of the protocols show an increase in power usage as the packet generation rate gets higher. PHASeR again gives the best performance in energy consumption, due to its packet loss, but LASeRs results also remain relatively low throughout. The analytical results for LASeR are accurate for low traffic levels, but overestimate the power consumption at higher levels. Overhead results highlight LASeR and PHASeRs low overhead. The analytical expression is also accurate for this scenario. MACRO also shows very low overhead, which is only slightly greater than that of LASeR and PHASeR, especially at higher traffic levels. Contrastingly AODV and OLSR have the worst overhead. Counter intuitively, the overhead for AODV and OLSR decreases as the traffic increases. This is due to the significantly diminished PDR and high delay times, meaning that a low quantity of overhead is used to deliver only a very low number of packets. LASeRs ability to cope with these high levels of traffic indicate that the additional redundancy created from the blind forwarding mechanism does not impede the protocols performance. Furthermore, the maintained high level of PDR illustrates how the route diversity enables the protocol to perform reliably.



(a)



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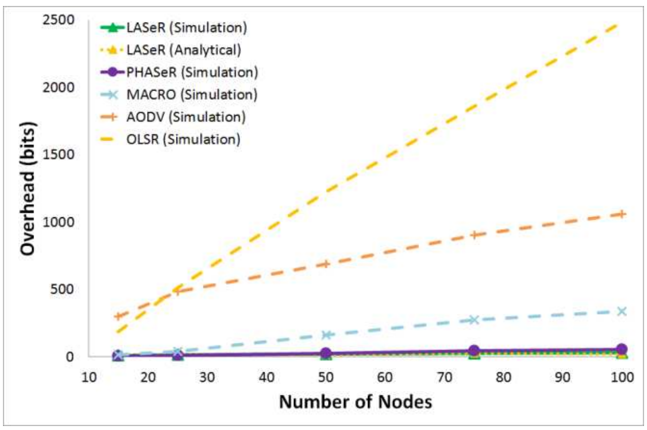

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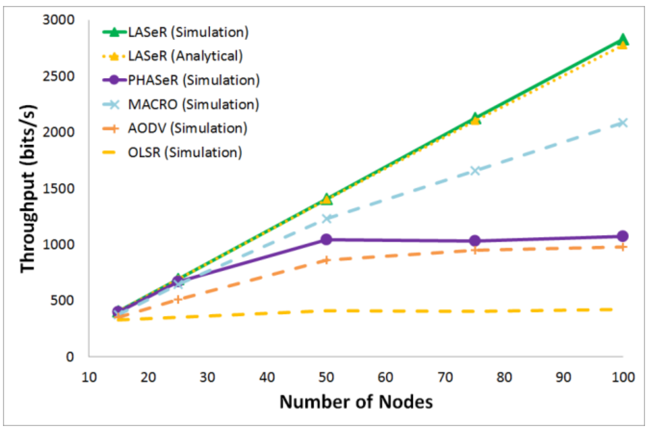

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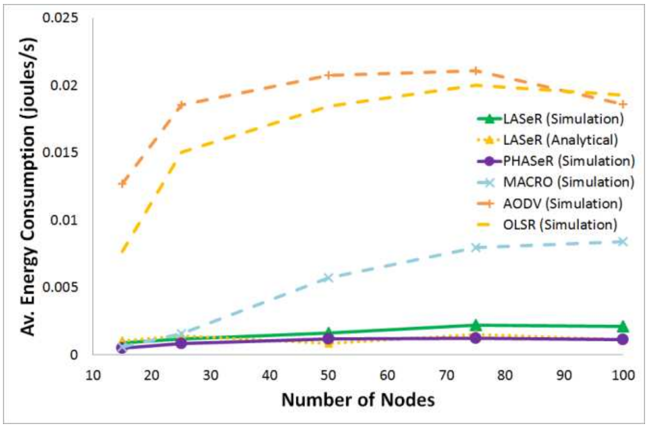
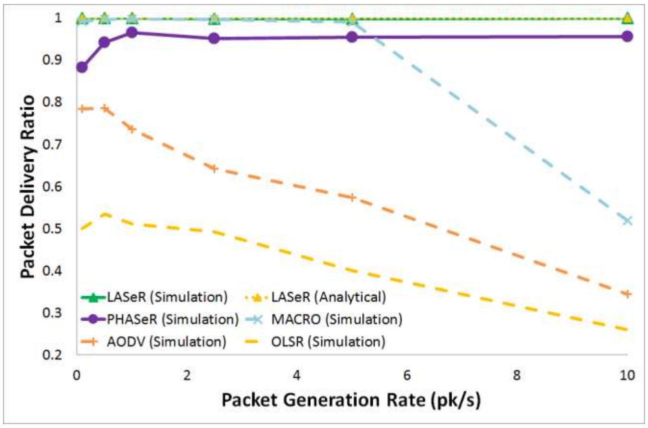
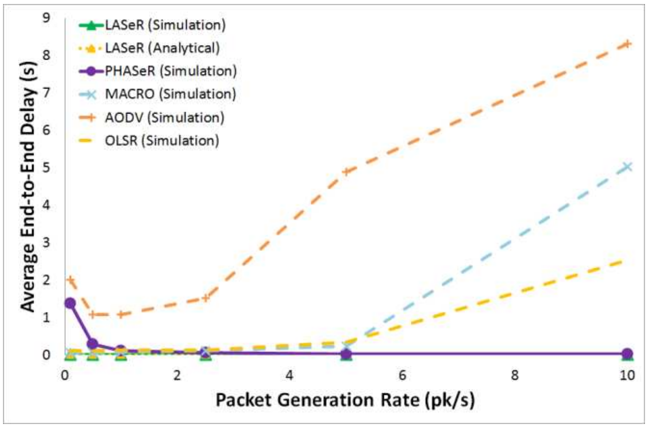


(e)

Fig. 4. Results for LASeR, PHASeR, MACRO, AODV and OLSR for numbers of nodes: (a) PDR, (b) Average End-to-End Delay, (c) Overhead, (d) Throughput and (e) Average Energy Consumption.



(a)



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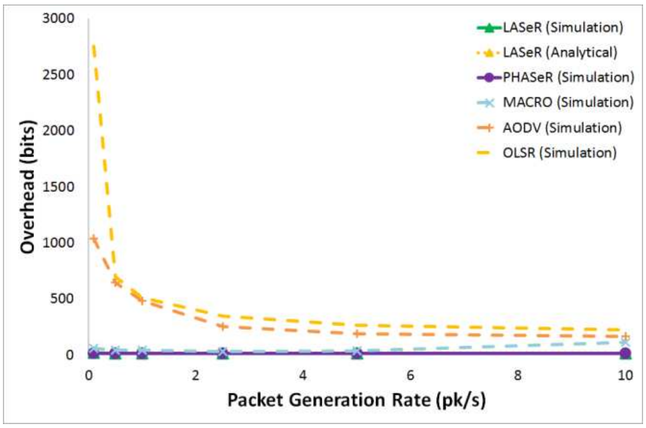

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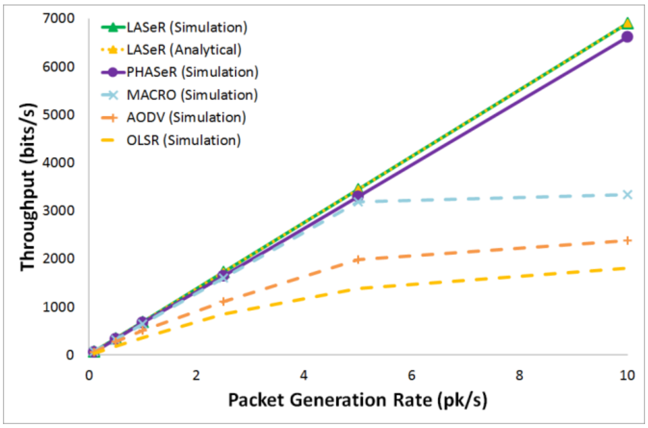

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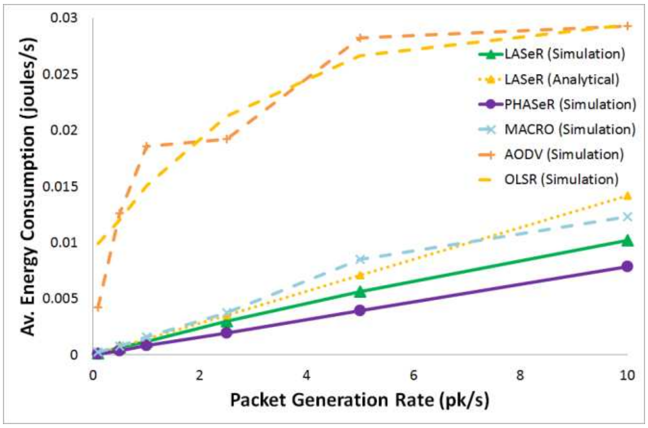

(e)

Fig. 5. Results for LASeR, PHASeR, MACRO, AODV and OLSR for varying packet generation rates: (a) PDR, (b) Average End-to-End Delay, (c) Overhead, (d) Throughput and (e) Average Energy Consumption.

VI. Conclusion

This paper has presented a geographic routing protocol, LASeR, designed for use in MWSNs. The protocol uses location awareness to maintain an up-to-date gradient metric in highly mobile environments. The use of blind forwarding inherently allows multiple routes for packets to travel along, creating a very robust method of routing that is ideal for coping with frequent topology changes. The robustness of LASeR is illustrated by the presented results, which were modelled on the terrain mapping application. Overall the results show a superior level of performance over the recent MWSN routing protocols PHASeR and MACRO, as well as AODV and OLSR. It has high PDR and low average end-to-end delay, making it reliable and fast. The overhead has also shown to be low, which gives LASeR a low level of energy consumption. These attributes make the protocol well suited to the target application. LASeRs outstanding results and robustness to a variety of scenarios suggest that the protocol may also be suitable for a large number of applications. Additionally, analytical expressions were derived and, after comparison with simulated results, show them to successfully characterise the protocols performance. Future work will focus on implementation of the protocol on a testbed of networked autonomous ground vehicles.

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