

EDLA Tradeoffs for Wireless Sensor Network Target Tracking

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Abstract—The number of active nodes in a WSN deployment governs both the longevity of the network and the accuracy of applications using the network's data. As node hibernation techniques become more sophisticated, it is important that an accurate evaluation methodology is employed to ensure fair comparisons across different techniques. Examining both energy and accuracy ensures a claim of increased longevity for a particular technique can be contrasted against its associated drop, if any, in application accuracy. This change can also be as a result of increased latency and the accuracy encapsulates many aspects of WSN performance in one metric. In this work, we detail the first in a series of simulation experiments designed to demonstrate the tradeoffs for a WSN and we employ mobility tracking as the application to benchmark accuracy. Additionally, we demonstrate experimental evidence for a potential adaptive mobility tracking protocol.

I. INTRODUCTION

For a typical WSN, the accuracy of an application and the longevity of the network will be inversely proportional to each other. This is due to the finite power reserves of the nodes and the desire for applications to have large volumes of fresh data to perform their calculations. A number of techniques have been proposed that can opportunistically hibernate sensors, such as CCP [1], but no work to date has focussed on a complete analysis of such approaches from both the accuracy and longevity perspectives. For instance, consider a claim that a particular hibernation technique can double the life of a WSN. Will its error double also?

In this work, we detail the first of a suite of experiments designed to analyse the performance of a WSN when nodes are hibernated. This first benchmark demonstrates the Energy-Density-Latency-Accuracy (EDLA) tradeoffs [3][2] that exist for a WSN where no node hibernation's occur in the network. In this case the WSN topology will be static and serves as a baseline in WSN performance for future experimentation. Hibernation techniques can then be evaluated by how much they increase longevity or decrease accuracy from this baseline. Various parameters of the individual techniques can be tweaked in order to achieve better accuracy or longevity. Crucially, by examining both QoS metrics neither one can be artificially increased to distort performance. The relationships identified here are not unique to mobility tracking applications, many potential WSN applications requiring a balance between energy consumption, density, latency and accuracy may also be able to exploit the results and trends identified here.

In addition, this work also demonstrates experimental evidence for the operation of an adaptive mobility tracking application. We examine the localisation accuracy of a typical WSN configuration with varying degrees of message latency, target speed and application deadline selection. When values for some of the parameters can be estimated i.e. target speed, it is envisaged that an adaptive protocol may be able to tune other parameters to optimise accuracy of the WSN.

This paper fits within the broad category of SAHNS, while the AHNS under consideration here is of a specialised nature i.e. configured for target tracking, the paper itself deals with broader issues of latency and Quality of Service of such a system.

In the next section we look at mobility tracking applications that are used in our experimental evaluation. We then take a closer look at the EDLA tradeoffs for a WSN. Following this, the system architecture is detailed, including the protocol stack used on each node. The experimental setup is then provided in section V, with the results given in section VI. We close with conclusions drawn from this experimentation as well as a discussion of how this work can form the basis for benchmarking future WSN performance under the EDLA tradeoffs in the presence of hibernating nodes.

II. TARGET LOCALISATION

The task of target localisation, is to transform the streams of sensed data from the WSN into co-ordinates that pinpoint the location of a target in the sensed area [6]. Two basic target localisation techniques are chosen for the application in this work, since they specifically do not require any prior characterisation of the target, making them generally applicable for many environments and many targets. They are the Weighted Average Localisation (WL) and the Maximum Signal Strength Localisation (ML). For the Weighted Average technique each sensor that is active will be able to sample the signal at its location and the larger the value, the greater its influence will be on the estimated location.

$$x_{target} = \frac{\sum_{i=1}^N signal_i^2 x_i}{\sum_{i=1}^N signal_i^2} \quad (1)$$

A similar equation is applied to the y co-ordinate to locate the source in the 2-dimensional area, and this technique has been adopted previously in [3] and [5]. The second localisation

technique adopted here is a simple, but effective method, which assigns the location of the maximum signal value sensed at an active sensor to the location of the target and has been used in [5]. Two techniques are applied here so that a broader sense of how the application performance is affected by latency, deadline and target speed can be presented.

In standard target localisation application [5], the nodes sample their sensors and forward their data to the base station either at a given time, according to a schedule or in response to a command. The base station can wait for all the data to reach it before calculating the targets position, however, in that time the target will moved a certain distance. The longer the time it takes for all the messages to reach the base-station, the greater the distance travelled by the target, leading to an increase in localisation error. For this reason, we analyse the effect of message latency on localisation accuracy.

In many cases all the data will not reach the base-station, due to failed or exhausted nodes, in which case a deadline must be chosen when the available data is used to make a decision. Selecting the appropriate deadline by which the decision is made, means messages received afterwards are discarded. This approach, in effect, limits the density of messages observed by the base-station. This deadline can be determined experimentally on a case by case basis or it may be possible to derive this value from a theoretical analysis of various hardware and software parameters of the WSN.

III. ENERGY-DENSITY-LATENCY-ACCURACY TRADEOFFS

The EDLA trade-offs refer to the four distinct performance characteristics *Energy*, *Density*, *Latency* and *Accuracy* of a WSN. As more *Energy* is consumed by the nodes, the operational lifetime of the network reduces. The *Density* refers to the number of nodes deployed in a given region to be monitored. When considering a WSN using a density maintenance scheme, such as CCP [1], the density is defined by the number of *active* nodes in the area. *Latency* of messages refers to the delay between the time a message is sent and the time it is received at its destination. Finally, *Accuracy* refers to the precision that an application can perform its task, using the WSN and its data. Each one of these is now examined in further detail.

1) *Energy*: The energy consumed by a node is due to the activity of a number of its components, such as transmission of data via the transceiver, executing instructions using the processor, storing program state in memory and sampling the sensors. Therefore, the amount of time a given node is active, the shorter its lifetime will be due to its finite power supply. This implies that energy and node lifetime are inversely proportional to each other. Hibernating a node consists of switching some, or all [9], of its hardware components into a low power sleep mode, where it consumes a fraction of the energy and thus can operate for an increased period of time. For a network as a whole, therefore, the energy consumed will be proportional to the number of active nodes or node density.

In addition to the energy saved at the hibernating node, further energy is conserved along the path its packets are

forwarded to the base station, through the absence of its data. The drawback of this is that while in hibernation, the nodes sensory data is not available, resulting in a blind spot in the network. In addition, the node is not available to forward messages from its neighbours and so an alternate path must be found. In summary, a trade-off exists between network longevity or energy consumption and the quantity or resolution of sensed data available, which will be explored later in this section.

2) *Latency*: For a sensor network, and indeed many other ad hoc networks of devices, a fixed bandwidth is available for the transfer of data between entities. As the number of nodes increases, more paths become available to route packets to their destination simultaneously, which in theory increases performance. Crucially, the routing component must be able to take advantage of these additional routes by continuously trying to improve its QoS. There will come a subsequent point, however, where the latency of transmission begins to increase proportionally to the number of nodes. This is due to additional contention for the wireless channel as the node density increases.

Such a trade-off has been observed and preliminary experiments have verified such a relationship [10]. This implies that adding some nodes can result in improved performance, in terms of latency, however, with too many nodes the network becomes saturated. In addition to contention for the channel, an increased number of nodes increases the probability for both collisions and also instances of the hidden terminal problem for local broadcasts, which together can not only increase latency through retransmissions but can also lead to lost packets [10].

3) *Accuracy*: The accuracy of an application is directly related to the networks ability to provide timely delivery of a sufficient density of data to it. When this is the case, it is assumed that the application will be able to perform its task to an appropriate standard, and therefore, accuracy is directly related to the density and latency of the WSN. A deficiency in either aspect will result in sub-optimal application performance, through either inaccurate inferences about the state of the environment or perhaps excessive delays in decision making. Application accuracy may not degrade uniformly with the competence of the WSN i.e. sharp declines or increases may result from slight variations in density or latency and so it may be necessary to finely tune the parameters of the network in order to achieve the desired accuracy. It is crucial that in selecting an application to benchmark a WSN, that its performance depends on both latency and density which is true for our target tracking application.

4) *Density*: From the previous three discussions, it is apparent that the single biggest factor in determining the performance of a WSN is the number of active nodes in the deployment. Ultimately, density drives the power consumption, network longevity, latency and resolution of data perceived by the application. However, the overarching responsibility of the WSN is to ensure the performance of the application. Therefore, the density must be chosen with a corresponding

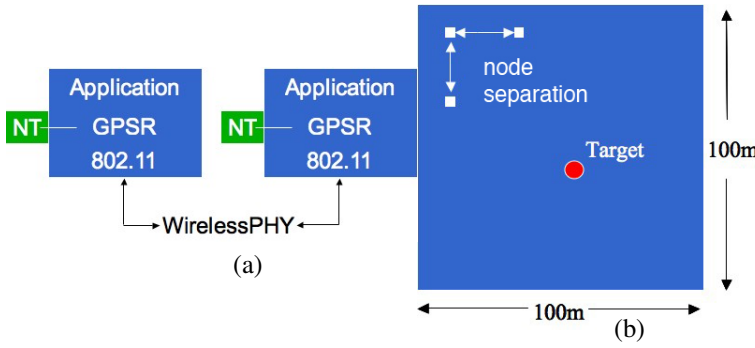


Fig. 1. (a) Protocol stack to demonstrate the effect of density on WSN accuracy and energy consumption. NT represents the nodes neighbour table. (b) Experimental Setup: The density of the deployment is varied by changing the inter-node separation. The target is within the environment and the magnitude of the signal received at each sensor is inversely proportional to the distance to the target.

accuracy in mind. This density must also be able to sustain the operation of the network for the desired lifetime.

Here we can see the trade-off in selecting an appropriate density, both accuracy and longevity must be maximised in tandem. Within this paper, we attempt to demonstrate characteristic trends that exist for varying densities and their effect on the accuracy and lifetime of the network. The experiments and results presented here will be relevant for many future deployments wishing to balance energy and QoS of a WSN.

IV. SYSTEM ARCHITECTURE

In order to deliver the aforementioned target tracking application we adopted a standard protocol stack, whereby equivalent layers communicate with each other on neighbouring nodes, figure 1 (a). When multiple nodes wish to communicate, they cannot do so at the same time due to interference on the channel, so a MAC layer is required in order to mediate the use of the channel and to retransmit failed packets. As such, the first layer on the WSN device for this system architecture will be the MAC layer, with direct control over the transceiver. For WSNs numerous approaches to this have been developed, including B-MAC [11], but we have opted for the in built 802.11 implementation provided with J-Sim [8]. J-Sim is a port of the successful NS-2 simulation environment to Java. It provides many of the protocols required to assemble a complete WSN application and is the simulation environment used for our experimentation. A MAC layer will typically use an RTS/CTS mechanism to manage communication between nodes but these control messages can be lost due to collisions in the channel, so perfect reliability is rarely achieved for an ad-hoc network in practice.

The next component of the stack provides the multi-hop communication for nodes out of direct transmission range of the base station. Greedy Perimeter Stateless Routing (GPSR) [7] is a multi-sink protocol, which uses the geographic location of the source, intermediate forwarding nodes and the destination to route the packet. The GPSR protocol [7], provided with J-Sim, will deliver the required forwarding for our

experimental purposes. While the choice of routing protocols can impact the performance of the WSN in terms of latency, we are not examining the latency characteristics of individual protocols and we leave an analysis of the impact of other protocols on our results to future work. The next component is the application resident on the nodes. This samples the sensed data at the node and relays it to the base station every ten seconds, for this set of experiments. A number of alternative configurations could harvest the data from the network, for example, the base station could flood the network with a command packet. Active nodes will respond with their data through the multi-hop topology. Another possibility could be for the base station to send a unicast message to specific nodes and only they reply. These variations are not considered here however.

At the base station a corresponding application layer receives data and calculates the location of the target based on the sensing information. With the fixed density deployed, the base station must use a timeout in order to balance the message latency with the number of readings received, and so a timer is started every ten seconds. After the timer expires, data which has reached the base station at that point is used to evaluate the location of the target in the environment. The longer the timer, the more data for the calculation, but the greater the subsequent distance the target will have travelled, potentially increasing error. For a density maintenance technique, increasing the number of active nodes will increase contention for the channel and therefore increase latency. The two protocols used to decide on the targets' location, ML and WL, operate with identical data, i.e. the time for the first protocol executing does not impact the timeout used for the second.

V. EXPERIMENTAL SETUP

As outlined previously, the simulation environment used for our experimentation is J-Sim. The simulated area for this set of experiments is defined as 100 meters x 100 meters with a variable node density, figure 1 (b). One of the primary reasons for selecting this setup is to allow the results to be generalised to large areas by concatenation of networks similar to this. For example, a 500m x 500m region could be configured using 25 instances of the setup used here in a 5 x 5 grid formation. The transmission range for each node is fixed at 25m resulting in a maximum hop count of 6 for the most outlying nodes.

The target in the environment is allocated a power of 1000 units and decays according to the inverse square law of distance. This model is applicable in many instances, including thermal radiation, light, sound and magnetic and gravitation fields, and has been used previously for similar experiments in [5]. It is initially located in the centre of the sensed area and takes a random walk around the area at the specified speed. It is assumed that no prior information is available about the targets' characteristics, however, for these experiments its maximum speed is limited to 10 m/s or 36 km/h. Under this setup, all of the nodes remain active and no hibernation of any nodes takes place. The purpose of the experiments, detailed next, is to demonstrate the precise trade-off between energy,

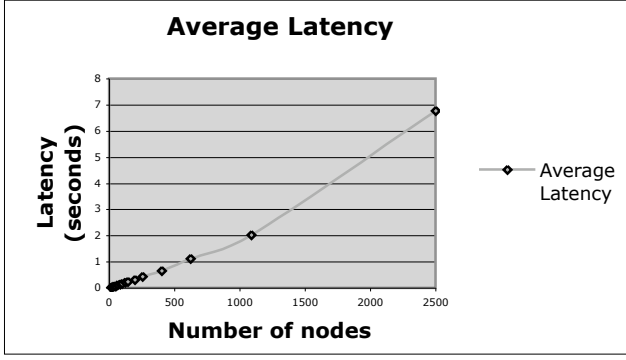


Fig. 2. The effect of density on the latency of messages reaching the base station.

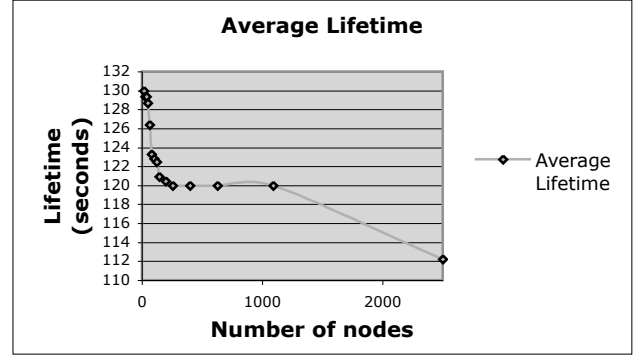


Fig. 3. The effect of density on the average lifetime of a node.

density and latency with application accuracy evaluating the networks competence.

VI. RESULTS

The roadmap for these experiments is as follows, firstly the effect of density on the latency of messages reaching the base station is examined. Density for these experiments is altered by changing the inter node spacing. Secondly, the effect of density on the average lifetime of a node is illustrated. Recall that these experiments do not hibernate nodes and so the experiments do not measure the energy saved through the node going to sleep. The next experiment explores the impact of the density and latency on a stationary target for the ML and WL techniques independently. Subsequent to this, the effect of target velocity is incorporated by demonstrating the effect of density on the accuracy of the localisation for different timeout values. This finally leads us to the optimality criteria for the EDLA tradeoffs for targets ranging from 0m/s to 10 m/s. The experiments demonstrate relationships and trends that are characteristic of a number of applications where latency, energy consumption and accuracy must be balanced by the selected density.

A. Latency

The relationship between density and latency can be seen in figure 2. A clear dependency can be seen here, as node numbers increase, the contention for the channel also increases. This causes messages to be queued for longer times at intermediate nodes, which increases the delay between the time the message is sent and the time it is received. Since we start off with a connected network, no gaps occur in the curve as would be expected if some nodes were unable to communicate with their neighbours.

B. Energy

The effect of increasing density on the average lifetime of a node is depicted in figure 3. As the density increases, the average lifetime of a node decreases due to the increased activity. This is the result of forwarding additional packets, overhearing of additional neighbours packets and the increased

probability for collisions, which requires costly retransmissions. This result demonstrates the requirement to only use the minimum number of nodes necessary to perform the purpose of the network.

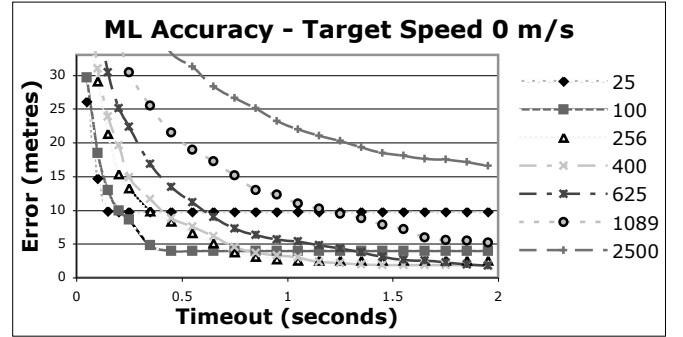


Fig. 4. The effect of density and selected timeout on the accuracy of the ML technique for a stationary target.

C. Accuracy

The strategy adopted in this set of experiments, is to first consider a stationary target for the localisation. Subsequently, target mobility is introduced by considering different target speeds. Finally, optimal criteria are deduced depending on the targets speed and additionally, relationships and trends are identified to predict how to define some of the WSN parameters for target speeds not under consideration here.

1) *Stationary Target:* The accuracy of the ML localisation approach for a stationary target is depicted in figure 4. A number of interesting points can be observed here. Firstly, the trends decrease toward a critical point and then completely flatten. This is due to the stationary nature of the target. Waiting for the maximum amount of data is advisable here in order to precisely localise the target. This is under the assumption that no other external deadline is enforced here. Secondly, the less dense deployments converge on their minimum error sooner than the more dense deployments. This is due to the fact that a

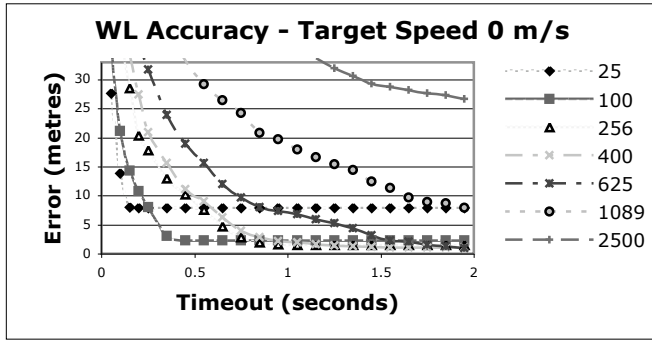


Fig. 5. The effect of density and selected timeout on the accuracy of the WL technique for a stationary target.

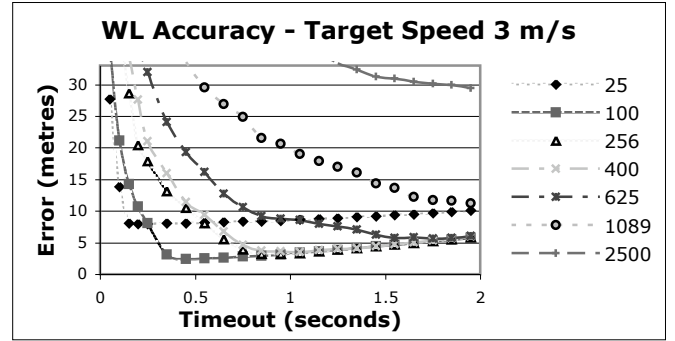


Fig. 7. The effect of density and selected timeout on the accuracy of the WL technique for a target moving at a velocity of 3 m/s.

greater percentage of the total deployment will reach the base station in a shorter time frame for less dense deployments.

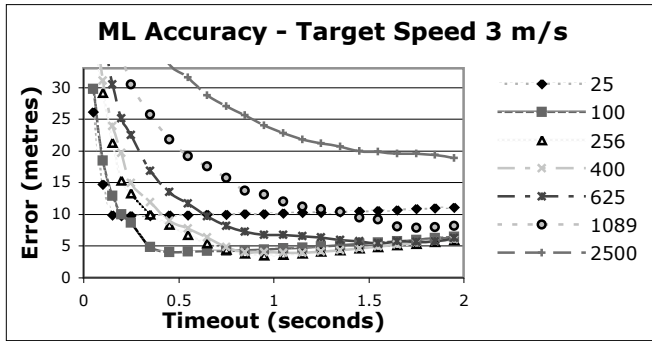


Fig. 6. The effect of density and selected timeout on the accuracy of the ML technique for a target moving at a velocity of 3 m/s.

Similar trends are observed in figure 5 for the WL technique, however a number of notable distinctions can be seen between the performance of the ML and WL techniques. Firstly, ML appears to outperform WL for a given timeout period. However, at the lowest, optimal point WL consistently outperforms ML. This is partially due to the fact that the WL technique consistently reaches its maximum accuracy at a slightly later timeout value than ML. This means that the small amount of extra data has more impact on WL than ML, which is not surprising given that ML uses only the single biggest reading while WL refines its solution as more data is received.

2) *Mobile Target*: The previous results are now augmented with a mobile target. The reason is that with a fixed delay in data reaching the base station, faster targets move a greater distance while the same density of packets are received at the base station. The effect of latency, introduced by the additional nodes will be magnified by faster moving targets and is demonstrated here. The first experiment uses a target moving with velocity 3 m/s, figures 6 and 7. Introducing the velocity removes the flattening of the curves as the timeout gets longer. This is due to the fact that the target is moving while packets

are en-route to the base station. A clear minimum point can now be seen for both ML and WL. This speed also results in a slight increase in error at the optimal timeout value as compared with the case for the stationary target.

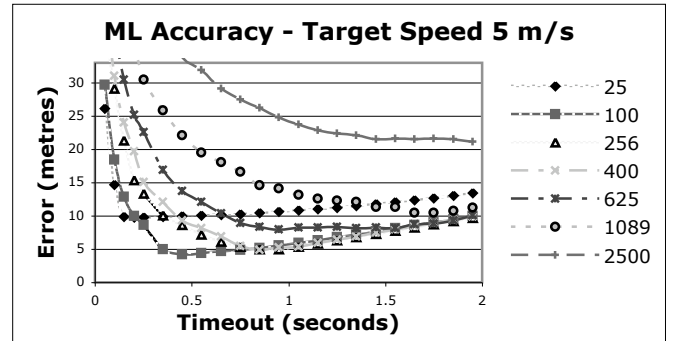


Fig. 8. The effect of density and selected timeout on the accuracy of the ML technique for a target moving at a velocity of 5 m/s.

As the speed increases further in figures 8 and 9 to 5 m/s, the target speed accelerates the upturn in the graphs after their optimal point. Additionally it increases the error at the optimal point and it also causes the optimal timeout to move to an earlier value. In order to verify these relationships, and to identify other trends, we now isolate the minimum error for both the ML and WL techniques. Based on this, the error, timeout, density, latency and node lifetime are now examined as a function of these optimal values.

3) *Optimal Criteria*: Figure 10 demonstrates the effect of the targets velocity on the optimal performance of the two localisation techniques. From this graph it is clear that the faster the target, the more difficult it is to localise. Additionally, the WL technique consistently outperforms ML for all target speeds. From figure 11, it is can be seen that as the target speed increases the optimal accuracy occurs at an earlier timeout.

Interestingly, for slow target speeds there is a considerable difference in the timeout for the ML and WL techniques, figure

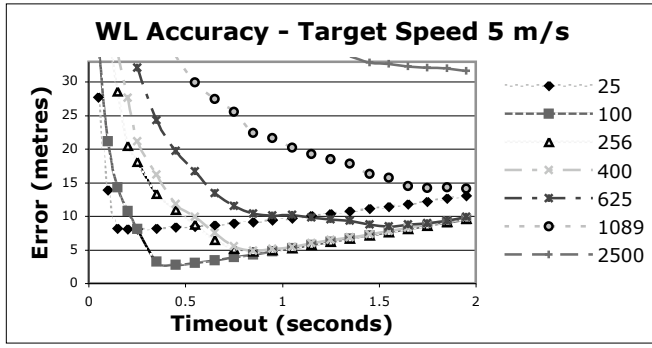


Fig. 9. The effect of density and selected timeout on the accuracy of the WL technique for a target moving at a velocity of 5 m/s.

11. This can be quite useful when an external deadline, other than optimal performance is in force. Under this condition and based on these experimental results it would appear that the WL technique can deliver its optimal solution at an earlier deadline than ML for slower moving targets. Additionally, the fact that there exists a correlation between target speed and timeout means that if an application can predict the speed of the target then it could possibly adapt its timeout value in order to deliver optimal performance. This would be useful however, only when the target is moving at constant velocity.

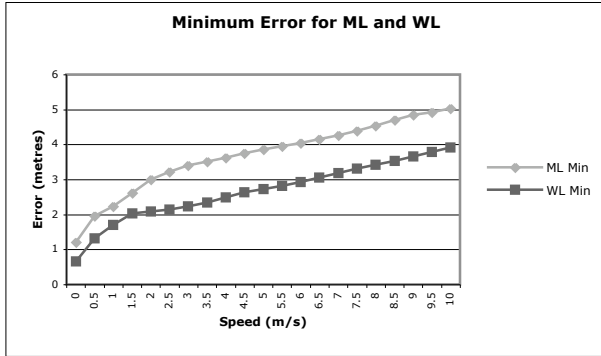


Fig. 10. Optimal error for the ML and WL techniques for varying target speeds.

Figure 12 shows the density of nodes that produces the optimal accuracy for varying target speeds. As demonstrated earlier, density and latency are related, therefore figure 13 has an identical shape to the density graph. An important result can be seen here. As the target speed increases, the number of nodes required to produce the optimal localisation accuracy decreases. The reason for this is that as the target speed increases, the application favours fresh data over large quantities of stale readings. This is shown in figure 13 by the decrease in latency as the target speed increases.

The impact of this on energy consumption in the network can be seen in figure 14. Remarkably, as the target speed increases the average lifetime of a node increases due to

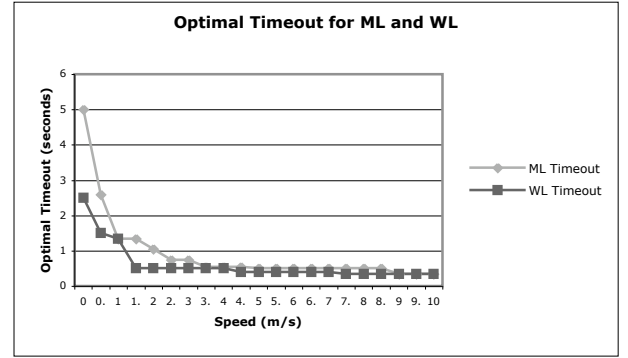


Fig. 11. The timeout, at which, the optimal error for the ML and WL technique occurs for varying target speeds.

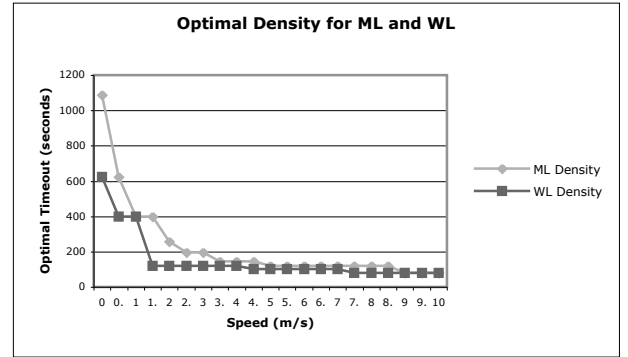


Fig. 12. The density, at which, the optimal error for the ML and WL technique occurs for varying target speeds.

the reduced density required for optimal performance. This result demonstrates that from both an accuracy and energy perspective, it is not desirable to simply deploy as many nodes as possible. This will be the case for many WSN applications where a balance of latency and density must be maintained. We have considered only the density of the hard deployment here, however the results can be generalised to a dense topology where a density maintenance scheme, such as CCP, is activating nodes according to a specified density. In this case however the average lifetime of a node should be increased due to the potential for the additional nodes to take over from exhausted sensors.

VII. CONCLUSIONS

In order to characterise the performance of a WSN, two primary metrics are typically of interest - longevity and accuracy. The range of experiments outlined here, evaluates a WSN through the performance of a target tracking application, which is particularly suited to the task due to the continual motion of the target while messages are en-route to the base station.

Specifically, the effect of density on latency, node lifetime and ultimately application accuracy is examined here. The tradoff between data volume and latency is managed through

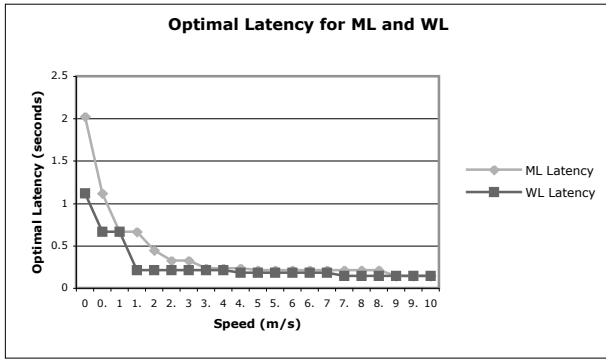


Fig. 13. Latency for the parameters where the optimal error for the ML and WL techniques occurs for varying target speeds.

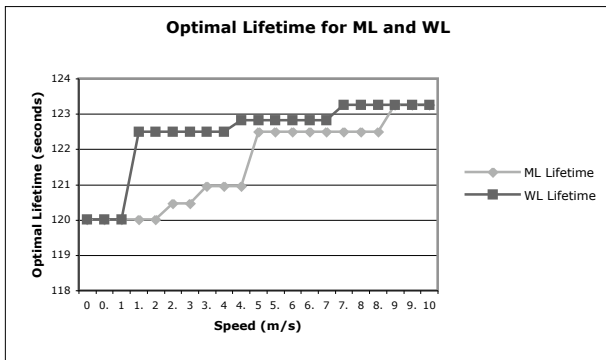


Fig. 14. The average lifetime of a node for the parameters at which, the optimal error for the ML and WL technique occurs for varying target speeds.

the selection of an appropriate application timeout and density, in order to achieve optimal system performance. Such tradeoffs are characteristic of applications that must receive an appropriate amount of data by a certain deadline in order to function correctly.

A number of interesting results have been obtained, including the fact that dense deployments are not always optimal. We have shown that the faster the target moves, the harder it is to localise, even using an optimal setup. The application accuracy for faster targets favours fewer nodes, resulting in less latency and an increase in node lifetime.

Since this work does not hibernate any nodes, it will form the basis of a benchmark, in terms of node longevity and WSN accuracy. Node hibernation techniques, such as CCP [1], can operate to increase the operational lifetime of the network. However, the impact of this on WSN accuracy can also be measured, meaning that a set of checks and balances are in place to ensure that a technique does not excessively sacrifice performance in order to claim a significant increase in energy saved or vice-versa. For example, the added latency due to the presence of the hibernation protocol's messages on the channel will impact the optimal number of nodes and the optimal timeout which in turn will impact the longevity of

the network due to the increased transmissions.

We propose to develop a framework for such an evaluation of power management protocols for WSNs e.g. CCP [1] or those based on interpolation [12]. This would allow new techniques to be plugged into the framework and evaluated according to the longevity and accuracy metrics.

Additionally, this work also demonstrated the effect both message latency and target speed has on the selection of the optimal timeout value for the localisation. If these values can be estimated for instance using timestamping or a crude velocity calculation, then the base station deadline could be tuned in order to deliver optimal accuracy across many latency values and target speeds. This is part of our ongoing experimentation and evaluation.

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