An RPL based Optimal Sensors placement in Pipeline Monitoring WSNs

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***Abstract*—Compared to an ordinary sensor network, Linear Sensor Networks (LSNs) has many applications in a number of areas such as surveillance and monitoring of international boundaries for illegal crossing, river environment monitoring and roads monitoring etc. However, due to linear topology and single path transmission of data, problems associated with LSNs is also significantly high. A linear topology increases the challenges associated with network reliability, connectivity and efficient energy management for sensors and actuators. It is therefore important to overcome these challenges prior to communication and reliable monitoring system that can be achieved in Wireless Sensor Networks (WSNs). This paper aims to investigate the linear placement of sensor nodes in LSNs using varying distance and its impact on energy consumption, packet delivery ratio, end to end delay, throughput and the Destination Oriented Directed Acyclic Graph (DODAG) construction time. The study is carried out using a uniform topology, where nodes are distributed linearly with increased distance, while the sink is placed at the end of the pipeline. Furthermore, the proposed study also fulfil the requirements of IPv6 Routing Protocol for Low-power and Lossy Networks (RPL) in LSNs. From the obtained results, it was evident that placing sensor nodes uniformly in LSNs at a distance of 10 meters provide optimum results in terms of Quality of Service (QoS).**

***Index Terms*—Internet of Things, RPL, Linear wireless sensor, uniform node placement.**

I. Introduction

WITH With the applications inherent in Wireless Sensor Networks (WSNs) a major driving force in development, the use of Linear Sensor Networks (LSNs) has emerged as an area of interest. An LSN becomes pertinent in situations where sensors are required to be lined up due to the particular application. This may be the monitoring of roads and bridges, however, the most obvious use is in pipelines [1][2][3]. This could may involve the monitoring of oil, gas or water, or sensors gathering information on the pipeline itself regarding temperature, water or oil flow, leakages, fire or pressure [1]. An added attraction of this application is in the security of transmission as opposed to cabled networks. With LSNs proven to be less prone to failure or sabotage [1].

Despite the obvious need for research in the application of LSNs, the difficulties inherent in improving these networks has resulted in a dearth of related work. As such, whilst the less complex implementation of a linear network topology may first indicate a simple implementation, this is not always the case. Whereas a complex network topology presents many different opportunities to improve the different facets of network performance, the same cannot be said for an LSN. An LSN presents little room for maneuver with regard to different combinations of Layer 3 metrics and algorithms to improve network performance. In areas such as data delivery and energy consumption

In simplistic terms, if the transmission range of any node only puts one node within range, as in Figure 1, then this node will always be the next hop, whatever routing metric is utilised. This then puts a vast amount of strain on nodes nearest the sink node, which will be the recipient of every single transmission in the network. This issue can be negated by increasing the transmission range (TX) of nodes, as in Figure 2, enabling neighbouring nodes in the linear structure to be hopped over. Whilst also bringing the possibility of utilising other metrics such as ETX or residual node energy. However, the cost of this pay-off is in increased energy consumption by each node. This occurs as radio signals are increased in order to improve said TX. This issue is highlighted in one study which proposes the routing protocol Minimum Energy Relay Routing (MERR) for LSNs. Within this study, the authors readily admit to seeing optimal routing as the least important metric in determining the efficiency of the protocol. With the minimum use of energy seen as the highest bound [4]. In return this also highlights another potential issue, with the previous study assuming uniform node placement. It is unlikely that this will always be the case.

The challenges inherent in improving performance levels in LSNs have been taken on in the past in different ways. The authors of one paper divided LSNs into groups based on density and the types of nodes in the network. Also seeking to inspire development of routing protocols which are more pointed in the direction of LSNs [3].

Another study attempts to negate some of the issues presented by LSNs by utilising unmanned serial vehicles (UAVs) in data collection from the sink nodes [2]. What is clear is that there is little consensus on how best to approach the issue of routing in LSNs.

However, given the recent standardisation of the IPv6 Routing Protocol for Low-power and Lossy Networks (RPL) [5], there is a requirement to evaluate the performance of this protocol in LSNs and to improve it where possible.

The reminder of this paper is structured as follows. In Sections 2 and, the state of art and overview about RPL is provided. In Section 4 related works are discussed. Section 5 presents the system model and the problem description are discussed. In section 6 performance evaluation and results discussion are provided. Finally in section 7 the paper is concluded and future recommendations have been made.

II. RPL ROUTING PROTOCOL OVERVIEW

In 2008 the IETF ROLL working group [6] was established with the purpose of creating a standardised routing solution for Low-power and Lossy Networks (LLNs). The result was the IPv6 Routing Protocol for Low-power and Lossy Networks (RPL) [7],

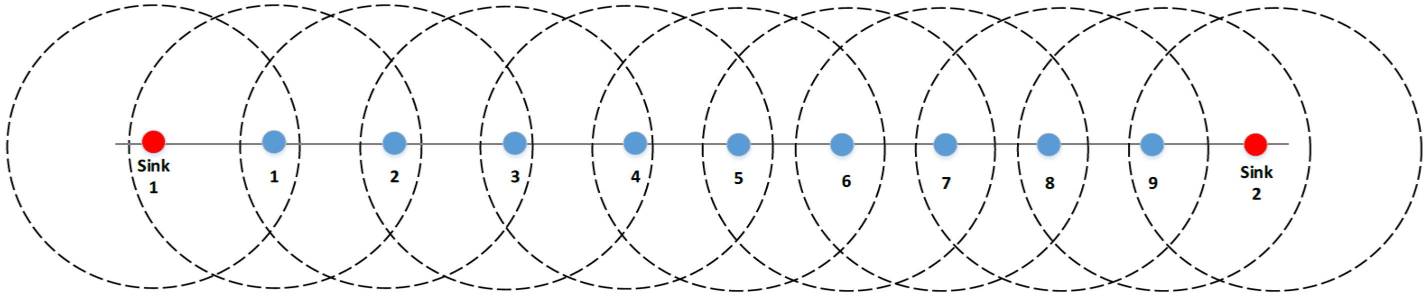

Figure 1: Single-hop Transmission Range

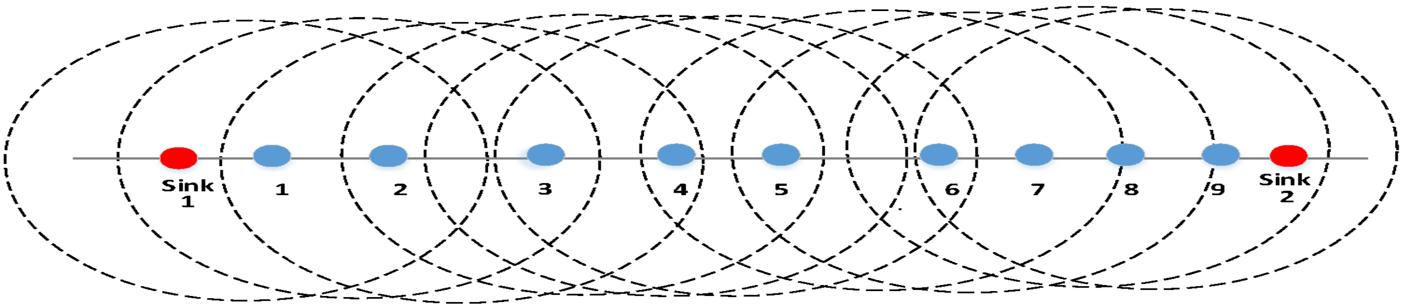

Figure 2: Multi-hop Transmission Range

a distance-vector routing protocol. RPL is, resultantly, standardised for use in WSNs such as LSNs. Considering the extreme locations in which LSNs may be utilized, the use of RPL is ideal given the allowances made for low-power devices and unreliable infrastructure. With links expected to go down frequently and the routing protocol designed to perform accordingly.

When considering the flexibility of routing integrated into RPL, with RFC 6550 [5][8] specifying the build of a destination oriented directed acyclic graph (DODAG), issues in consideration of LSNs become apparent. A DODAG is generally considered as a logical topology placed over a physical network. However, in the case of an LSN the logical topology is generally the same as the physical topology, therefore negating the benefit of a node being a member of multiple DODAG instances. In this case the Objective Function (OF) [9] according to which the DODAG is built becomes important, especially regarding the use of a particular routing protocol. In this case The Minimum Rank with Hysteresis Objective Function (MRHOF) [10] is of interest with its use of metrics and constraints. Although the OF itself can also be the sole driver n the DODAG build, such as in "RFC6552: Objective Function Zero" for RPL [10]. As the default OF for RPL, The Objective Function Zero (OF0) [9] does not actually utilize a routing metric. Instead using the rank of the node upon which to determine the next hop, whilst also utilizing feasible successors in the event of preferred successors not being available. This, generally, results in performance not dissimilar to when the hop-count metric is used. As such, the use of actual metrics such as Link Quality Level Reliability or ETX are recommended instead[11]. This requires the use of MRHOF [10], which unlike OF0 uses metrics to reduce the distance to a destination. These are carried in the metric container, this advertised in the DAG container option carried in DODAG Information Object (DIO) messages[8]. These used for DODAG discovery by advertising downwards in order to build routes upward towards the DODAG root, generally the sink node [11]. In the event that no metric is advertised, the default metric is ETX, the Expected Transmission Count [10]. However, many metrics are defined for use by MRHOF in "RFC6551: Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks" [11] as well as ETX, such as Hop Count, Link Latency, Node Energy or Throughput.

III. RELATED WORK

Strategic placement of nodes is extremely crucial to satisfy contemporary performance metrics such as energy efficiency, network lifetime, coverage and connectivity. This issue is highlighted in one study, which proposes the routing protocol Minimum Energy Relay Routing (MERR) for LSNs. Within this study, the authors readily admit to seeing optimal routing as the least important metric in determining the efficiency of the protocol. With the minimum use of energy seen as the highest bound [4]. In return, this also highlights another potential issue, with the previous study assuming uniform node placement. It is unlikely that this will always be the case. The challenges inherent in improving performance levels in LSNs have been taken on in the past in different ways. The authors of one study divided LSNs into groups based on density and the types of nodes in the network. Also seeking to inspire development of routing protocols which are more pointed in the direction of LSNs [3]. Another study attempts to negate some of the issues presented by LSNs by utilising unmanned aerial vehicles (UAVs) in data collection from the sink nodes [2]. What is clear is that there is little consensus on how best to approach the issue of routing in LSNs. There are very few works related to node placement in LSN, they mainly focus on placement of sinks in overall LSN deployment. Whereas, focus of our work is mainly on placement of sensors because they have limited energy resources and have higher impact on network performance. Moreover, these studies do not analyse the impact of nodes location in term of quality of service metrics other than network lifetime, which we do in this work. In addition to this,

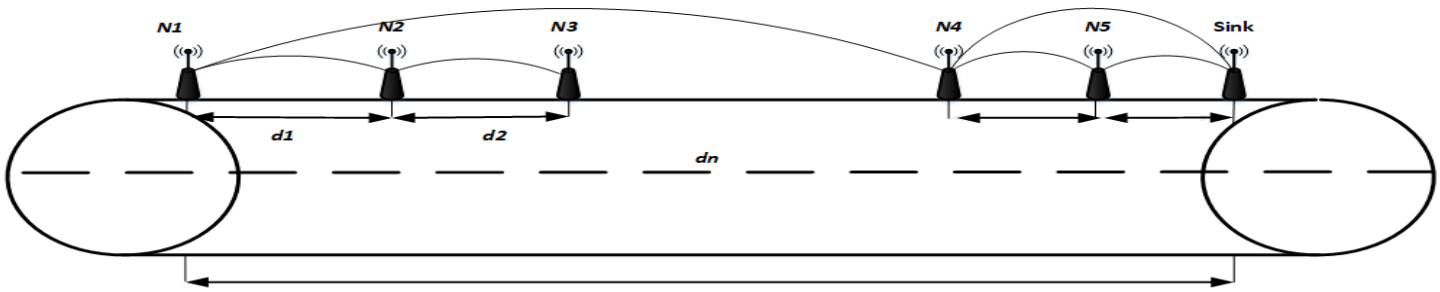

Figure 3: Linear Topology

the performance evaluation in this study carried out based on RPL as a routing protocol, which add more uniqueness to our work.

IV. SYSTEM MODEL AND PROBLEM DESCRIPTION

As a system model a pipeline monitoring sensor network that contain N number of nodes and a sink is considered as illustrated in figure 3. The nodes are responsible for detecting, collecting and processing the monitored information and send it to the sink for further processing. The sink is located in one end of the pipeline. Let N be the number of sensor nodes along the pipeline and di be the distance between node i and (i+1), $i = 1, .., n$. Then the length of the pipeline is

$$\sum_{i=1}^{N} d1 = L \tag{1}$$

The nodes communicate in multi-hop fashion with the same transmission range. For the data forwarding between individual nodes and the sink RPL with Expected Transmission Count (ETX) as an objective function is employed as a routing protocol. The use of the Expected Transmission Count (ETX) metric in RPL over LSN will help the nodes to use more reliable paths that is based on minimum transmissions of a packet to reach the sink.

Assuming different distance di between nodes, nodes placed at a larger distance from sink might suffer from additional overhead and overload in transmitting the packets, which in return might lead to performance implications in throughput, reliability issues and energy consumption.

V. PERFORMANCE EVALUATION AND DISCUSSION

In this section the simulation metrics and the performance evaluation are presented. The simulated topology consists of 24 sensor nodes and 1 sink positioned along the pipeline of length 1000m in a linear sequential manner. The sink is positioned at the edge of the pipeline. The experiments is carried out so that an optimal spacing between nodes under uniform and linearly sensor placement schemes with increasing distance can be provided. In addition to this the performance of RPL under the same conditions can also evaluated. The evaluation has been carried out using a customized version of Omnet++ network simulator that includes an implementation of the RPL routing protocol designed by the authors. The transmission and an interference range are set to be of 100 meters. The Expected Transmission Count (ETX) [12] is used for calculating the node ranks and selecting the preferred parent, so that stability in the network topology is built. Further parameters are provided in Table I.

Table I: SIMULATION PARAMETERS.

Parameter Name	**Values**
Simulation Area	1000 x 1000 m
Number of nodes	First Scenario 25
Number of nodes	Second Scenario 200, 300, 400, 500
Number of Packets	60 bytes
Simulation time	300s
Mote Type	Tmote Sky Mote
Mac/Adaptation Layer	IEEE802.15.4/6LoWPAN
Radio Model	CC2420
Transmission Range(m)	30 m
Interference Range	25 m
Routing Protocol	RPL
Mode Of Operation	None Storing mode
Rank Metric	ETX
Nominal Capacity	1000mAh
Battery Capacity	1000mAh
Voltage	3 V
Node Distribution	Linear Distribution

The evaluation has been carried out in terms of the following metrics:

1) The average power consumption in the network in milli-watts (Power Consumption (mW)).
2) Packet delivery ratio is the measure of the received packet by the sink over the number of packet sent by the source nodes [9][10][13].
3) End to end delay is the measure of the total time needed to transmit a packet over all flows in the network in millisecond. [9][10].
4) The average throughput is measure of number of packet received to the number of packet sent over the simulation time in bits per second [9] .
5) DODAG construction time is the time needed for the nodes to join the DODAG.

A. Distance Variation

In the simulation scenario the distance between each nodes starts at a value of 10 meters then varied by 5m meters to a maximum of 40 meters. UDP packet of 60 bytes is sent by all nodes to the sink. To generate accurate results an average value of 10 runs with different seed values over a simulation duration of 300 seconds is taken.

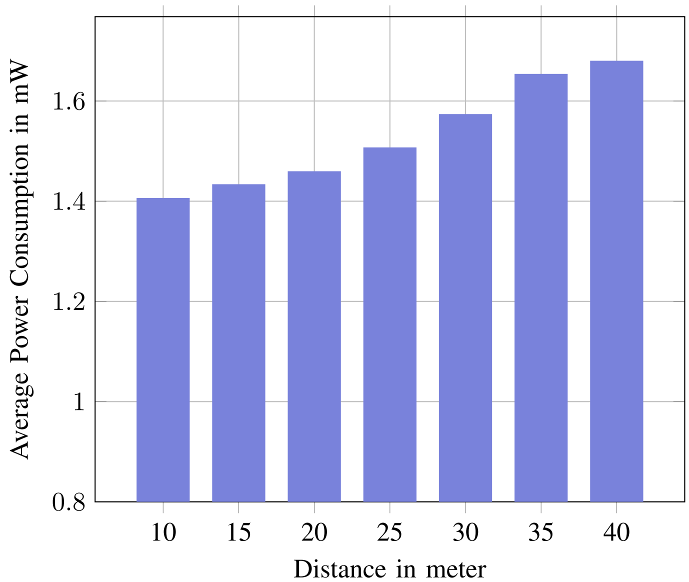

Figure 4: The average Power Consumption vs Distance

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Fig. 4, presents the average mean power as a function of the distance between nodes. It can be observed that increasing the distance will result in an increase in the power consumption. The figure indicates that placing the node in 10 meters distance from each other leads to the least amount of consumed power and the longer the distance between nodes is the more power is consumed. The power consumption reach the highest level at a distance of 40m. This increase is due to the fact that the transmitting from a larger distance to the sink might lead to overhead and overload in delivering data packets.

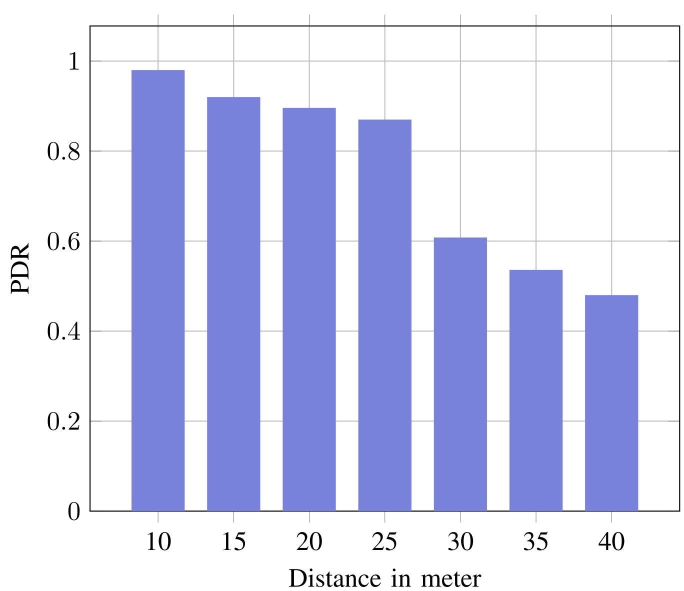

Figure 5: The Packet Delivery Ratio vs Distance

Figure 5 illustrates the PDR as a function of distance between nodes along the pipeline. The delivery ratio of 98% in 30 meter distance has achieved the highest level compared to the other distances followed by a delivery ratio of 92%, 89% and 87% for 35m, 20m and 40m respectively. While at distance of 15m and 25m the PDR has dropped to 60% and 53% respectively. At a distance of 20m the PDR has registered the lowest value of 48% only.

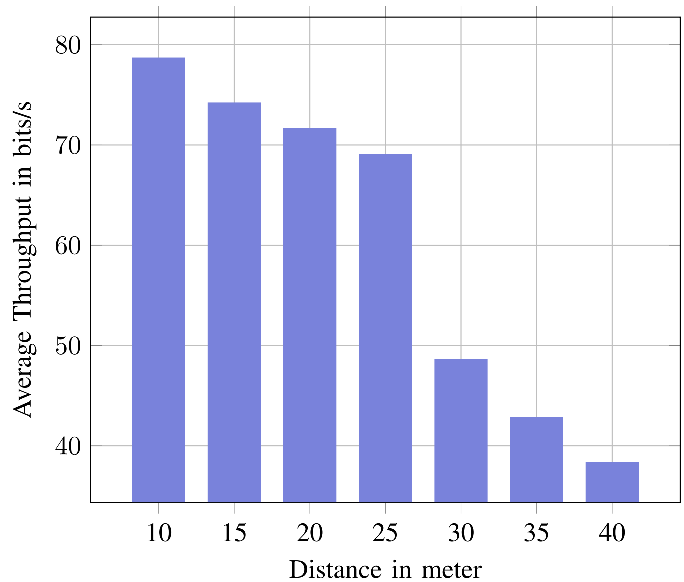

Figure 6: The average Throughput vs Distance

Figure 6 shows the results obtained for the throughput as a function of distance in bit/s. From which it can be observed that the distance of 10m has achieved the highest throughput of 78.72 bit/s. Surprisingly the throughput at 15m has shown significant drop. At distance of 20m, 25m and 30m the average throughput increases outperforming 15m, 35m and 40, but still less than the throughput in 10m distance. It can be concluded that placing the node at 10m distance from each other is the optimum in terms of throughput.

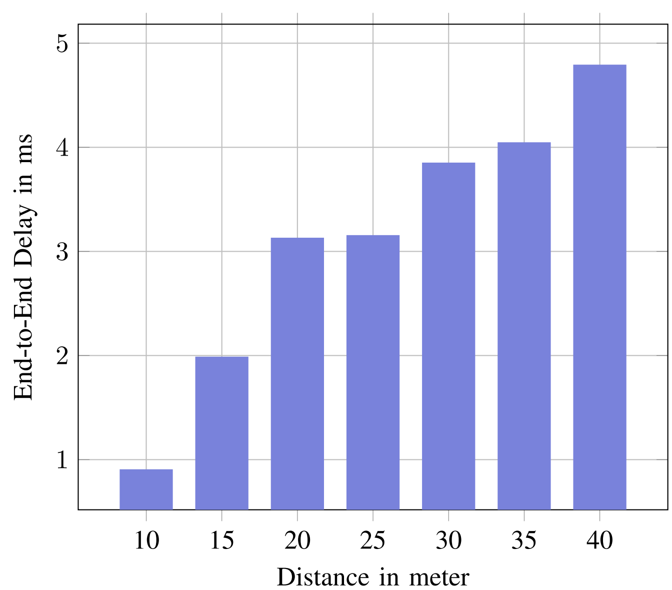

Figure 7: The average End-to-End Delay vs Distance

Referring to figure 7 the average end to end delay in packet transmission as a function of distance is presented. It can be observed that at a distance at 10m the end to end delay has recorded the lowest level. Starting at a distance of 15m the end to end delay increases gradually till it reaches its highest value at 40m.

B. Network Density

In the second scenario, we have increased the number of nodes starting from 100 to a maximum of 500 nodes. This required also increasing the length of the pipeline to 20000 meters to accommodate the number of nodes. The simulation time is set to 1 hour to enable enough time for all node to join the DODAG. The distance between each nodes starts at a value of 10 meters then varied by 5m meters to a maximum of 40 meters. UDP packet of 60 bytes is sent by all nodes to the sink. To generate accurate results an average value of 10 runs with different seed values. This scenario should help in studying the impact of the number of nodes and distance would affect the energy consumption, PDR, throughput and delay in a linear pipeline. Figs. 8, 9, 10, 11 and 12 present an inter-distance study for various number of nodes in terms of the average power consumption, PDR, End-to-End delay, and DODAG construction time.

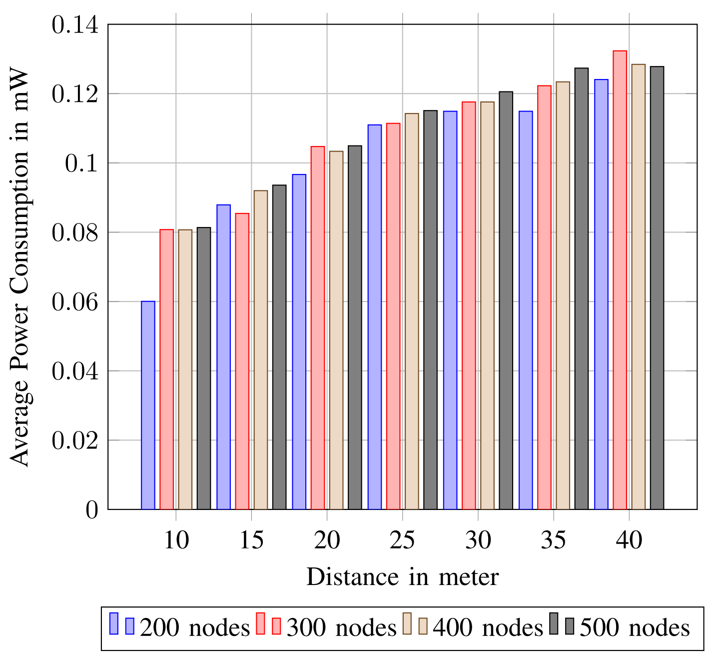

Figure 8: The average Consumption vs Distance for different node number

Figure 8 represents the power consumption for different distances and increasing number of nodes. It can be observed that in a distance of 10 meters the power consumption is the lowest. The power consumed is increased by increasing the distance and the number if nodes. This happens because the number of hops needed to reach the destination is increased by increasing distance, and hence the average power dissipated is decreased, but this is valid up to an optimum value, which is here the distance of 10m. It is clear from the figure 12 that there is an inverse relationship between the distance and the power consumption while there is a direct relationship with the delay and DODAG construction time. Indeed, the lesser is the minimum DIO interval, the higher is the energy consumption.

From figures, 9 and 10 the packet delivery ratio and throughput decrease with increasing the distance, and increase as the number of nodes increases. Here also we can conclude that 10 m distance is an optimal distance that can accommodate up to 500 nodes. This also can be justified by considering figures 12, where it shows shorter the distance the less time it takes for nodes to join the DODAG. As consequence immediate packet transmission can start.

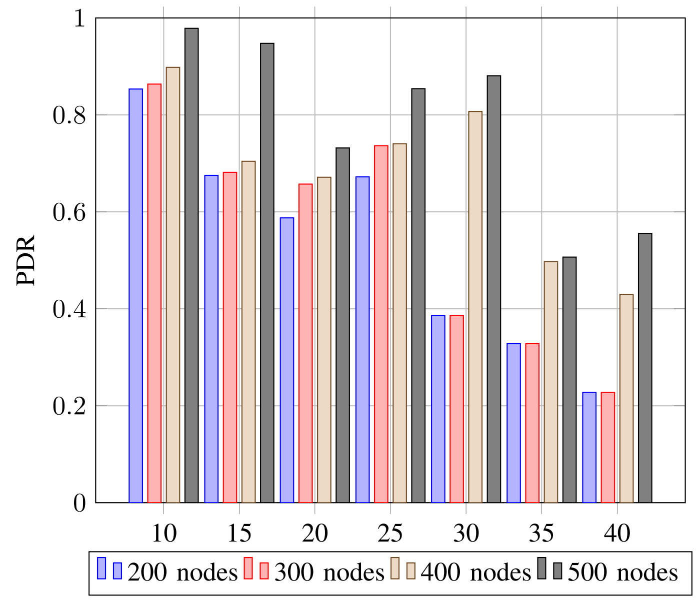

Figure 9: The Packet Delivery Ratio vs Distance for different node number

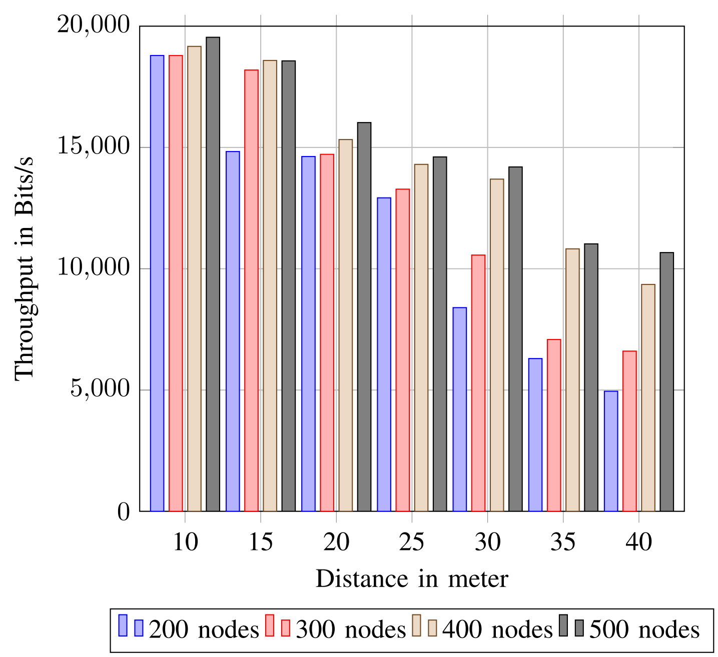

Figure 10: The Throughput vs Distance for different node number

A Poor packet delivery rate is an ingrained problem. It may be caused by many reasons, such as interferences, collisions, signal attenuation etc. The figure 9 illustrates the delivery ratio according to different distance and node density that are classified to their Euclidian distance from each other and from their sinks. The path cost selection is based on the OF with ETX metric, which unsurprising gives the best overall results in terms of power consumption, PDR and throughput. However, this comes at the cost of increased delay due to the probing packets required to calculate the ETX metric. In addition, the results shown in figure 12 is applicable to justify the poor delay when the distance increases.

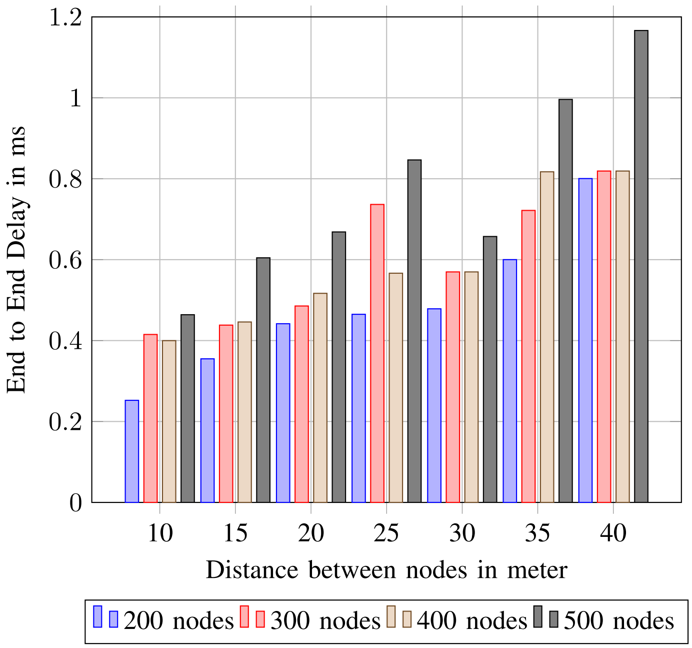

Figure 11: The The End-to-End Delay vs Distance for different node number

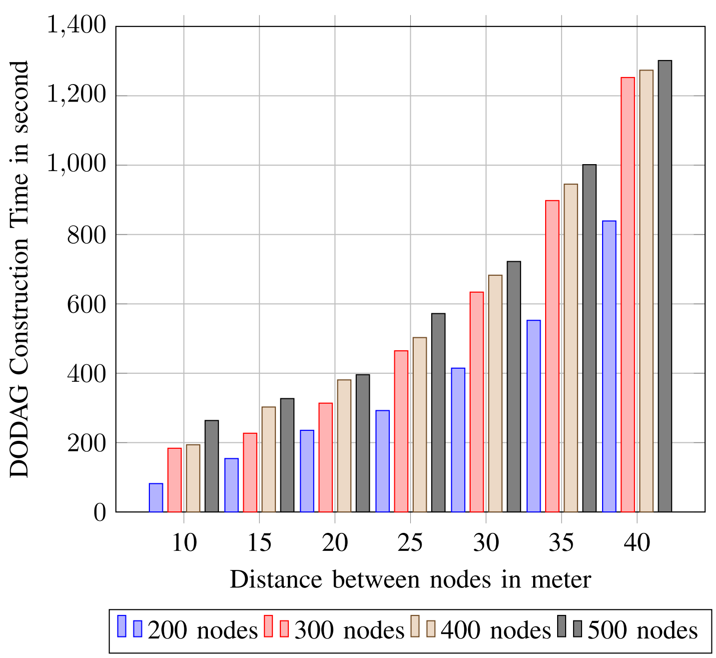

Figure 12: DODAG Construction Time vs Distance for different node number

VI. Conclusions and Future Work

This paper has highlighted a research carried out to investigate the impact of node placement in a linear sensor network (LSN) by placing the nodes uniformly a long a pipeline. The study based on increasing the distance between nodes, while placing the one sink at the end of the pipeline. The nodes communicate in multi-hop fashion with the same transmission range. For the data forwarding between individual nodes and the sink RPL with Expected Transmission Count (ETX) as an objective function is employed as a routing protocol. The study evaluate the performance in terms of power consumption, throughout, PDR and end to end delay. The findings have shown that the increasing of the distance between nodes has important performance implication in terms of the studied quality of service metrics. The shorter the distance between nodes the better the performance is. It can be suggested with great confidence that a distance of 10m has achieved a significant level of performance and can be considered as the optimum solution for node placement in an LSN. In the future it is planned to look at linear network from a routing prospective in LSN by conducting further study on RPL performance compared to the traditional standards, but also within RPL itself by using different objective functions to determine the best path.

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