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A Comparative Study of Mobility Models for Wireless Sensor Networks

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Abstract: Wireless sensor networks consist of hundreds or thousands of small, lightweight and low-powered sensor nodes that are deployed in the area of interest to collect information in an unattended manner. Since sensor nodes have limited battery, many research papers proposed techniques to enhance the performance and lifetime of wireless sensor networks. Using energy rich mobile sink to collect data from static sensor nodes is one of the techniques that can be used to improve the performance of wireless sensor networks. As a result, several mobility models were proposed to achieve this goal. In this study, we aim to study the performance of wireless sensor network under three mobility models for the mobile sink namely, depth first based mobility model, random waypoint mobility model and Gauss Markov mobility model. Consequently, ns-2 simulator is used to study the performance of the network under different scenarios and speeds of the mobile sink. Additionally, end-to-end delay, throughput and packet delivery ratio are the performance metrics considered in this study to measure the performance. Finally, AODV routing protocol is used to route messages from their sources to the mobile sink.

Keywords: Wireless Sensor Networks (WSNs), Mobility Models, Routing, Mobile Sink

Introduction

Recent developments in the field of communications and electronics have made it possible to design and manufacture cheap, small and lightweight sensor nodes. Batteries are the only source of energy used by sensor nodes, since they can be deployed in an unsystematic manner i.e., randomly to form a Wireless Sensor Network (WSN) and are required to operate in inhospitable environments. Furthermore, these sensor nodes use wireless links in order to communicate with other sensor nodes and to report sensed data. Since sensor nodes have limited energy, they must use it wisely in order to prolong their lifetime thus, the entire lifetime of the network is increased. Consequently, self-configuring and fault tolerance properties preserved WSNs. Therefore, deploying mobile sink node or nodes that are responsible for collecting sensed data from static sensor nodes is one of the methods that can be used to reduce energy consumption of static sensor nodes and to maintain self-configuring and fault tolerance properties of WSNs (Kartakarte *et al*., 2013; Taleb *et al*., 2014; Pushpa *et al*., 2011; Bai and Helmy, 2004).

A sensor node is composed of three subsystems. The first subsystem is for carrying out computation. The second one is used to give a sensor node the ability to sense and obtain data from the environment in which it is deployed. Finally, the third system is responsible for communication thus, a sensor node is given the ability to communicate in order to report data. The amount of energy consumed by the first two subsystems can be neglected when compared to the amount of energy consumed by the third subsystem. As a result, it can be concluded that to reduce the energy consumption of a sensor node attention must be paid to the subsystem responsible for communication in order to reduce the amount of energy it consumes. Say it in another way, the amount of energy consumed when communicating or sending packets is dependent on the distance between source and destination. Consequently, if the distance between the source and the destination is increased the amount of energy required for communication is increased. Therefore, if sensor nodes are limited to send data for small distances only, the energy consumed by the third subsystem can be reduced (Patel *et al*., 2007).

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As a result, single-hop communication can be substituted by multi-hop communication. Therefore, static sensor nodes can make use of their neighbours and use multi-hop communication in order to convey their messages to the mobile sink or the base station. Since the distance between a sensor node and its neighbours is usually smaller than that between a sensor node and the based station, the amount of energy consumed in communication by a sensor node is reduced. However, messages have to visit multiple intermediate nodes in order to reach its destination which increases the delay. As a result, the performance of the network might get affected when considering parameters such as end-to-end delay and success rate. Subsequently, combining the use of single-hop and multi-hop communication can help. So, a static sensor nodes will use single-hop communication to send data to the mobile sink if the mobile sink is in its vicinity or neighbourhood. Conversely, multi-hop communication or routing is used when a static sensor node needs to send data or messages to the mobile sink that is outside its neighbourhood or communication range.

Although deploying a mobile sink in WSNs can contribute in enhancing energy efficiency and improving coverage, the performance of the network and the routing protocol might get affected and downgraded especially when having a mobile node or nodes moving at high speeds within the network. To elaborate, the movement of a node from one position to another will change the neighbourhood information of other static sensor nodes. As a result, updates must be initiated by the routing protocol in order to adapt to changes in the topology. When the mobile sink is moving at high speeds, the routing protocol has to initiate the update process many times. As a result, most of the bandwidth and nodes energies will be consumed by communicating control information rather than reporting data to the mobile sink. Hence, it can be concluded, the mobile sink must move in the network at a reasonable speeds and give the routing protocol the ability to adapt to changes in topology and paths in the network (Pushpa *et al*., 2011; Murthy and Manoj, 2004).

In this study, we study the performance of three mobility models and propose using a single mobile node that will move according to a specific mobility model to collect data from randomly deployed static sensor nodes. Three mobility models, namely depth first based mobility model, random waypoint mobility model and Gauss Markov mobility model, are studied in this study and the mobile sink will be moving according one of them in each scenario. In other words, the performance of the network is studied and measured when the mobile sink is moving in the network under different speeds according to the depth first based mobility model for different network sizes. After that, the mobility model is changed and the mobile sink will be moving based on the random waypoint model according to same speeds and networks sizes used for the first model. Finally, the same network sizes and speeds are used to study the performance of the network when the mobile sink moves according to the Gauss Markov mobility model. Furthermore, throughput, success rate and end-to-end delay are the parameters used to study the performance of the above mentioned mobility models using the NS-2 simulator.

To elaborate, this paper aims to compare the performance of the depth first based mobility model, which was proposed by the authors of this paper in (Anas and Tareq, 2014), with that of Gauss Markov and random waypoint mobility models. Moreover, the performance of the three models will be studied under different parameters and different network sizes.

Hence, the main contribution of this paper can be summarized in the following points:

1. Simulating the wireless sensor network under different scales, while the mobile sink is moving according to different mobility models with different movement speeds
2. Analyzing the impacts of the different scales, different sink mobility models and different movement speeds of the mobile sink on the performance of the wireless sensor networks using the same routing protocol

The rest of this paper is organized as follows: In Sec. 2 the related work is discussed including the routing protocol used and the mobility models studied. Performance metrics used and simulation scenarios are explained in Sec. 3 and Sec. 4 respectively. Results are discussed and explained in Sec. 5. Finally, the paper is concluded in Sec. 6.

Related Work

According to (Traynor *et al*., 2006; Anas and Tareq, 2014), sensor networks can be defined as a systems that is composed of a huge number of static sensor nodes that can be deployed randomly in order to study and monitor the area of interest by measuring different parameters such as temperature, pressure and humidity and so on. Several research papers have proposed different mobility models that are based on deploying single or multiple mobile sink nodes within the network in order to collect data from static sensor nodes.

Therefore, existing mobility models in literature can be classified into two main categories where the first category is called heterogeneous mobility models and the second one is named homogenous mobility model (Taleb *et al*., 2013). As the name implies, heterogeneous mobility models are based on the presence of two categories of nodes within the network; the first type of nodes is composed of static sensor nodes that are responsible for monitoring and collecting information about the phenomena being studied. On the contrary, the second category of nodes is made up of a mobile sink node that is expected to move and travel through the network and gather data that have been collected and sensed by the static sensor nodes (Anas and Tareq, 2014; Taleb *et al*., 2013).

In contrast, homogeneous mobility models are based on having nodes of the same type in the network. To elaborate, the network will be consisting of a group of mobile nodes adopting and using the same mobility model. Furthermore, these mobile nodes will collaborate in order to monitor the area of interest and collect the required information. Worth mentioning, in some cases all the nodes in the network will be mobile while in other cases only a subgroup of sensor nodes are mobile and have the ability to move from one location to another (Anas and Tareq, 2014; Taleb *et al*., 2013).

Note that each of the previously mentioned categories can be further divided into different subcategories that are summarized in Fig. 1 which is adapted from (Bai and Helmy, 2004) and (Taleb *et al*., 2013). Say it in another way, heterogeneous mobility models can be divided into four subcategories namely; random models, controlled models, predictable models and geographic models. On the other hand, homogeneous mobility models can be further classified into controlled models and random models where the random models can also be divided into totally random and partially random subcategories (Taleb *et al*., 2013). Examples of mobility models that fall under each category are provided in Fig. 1.

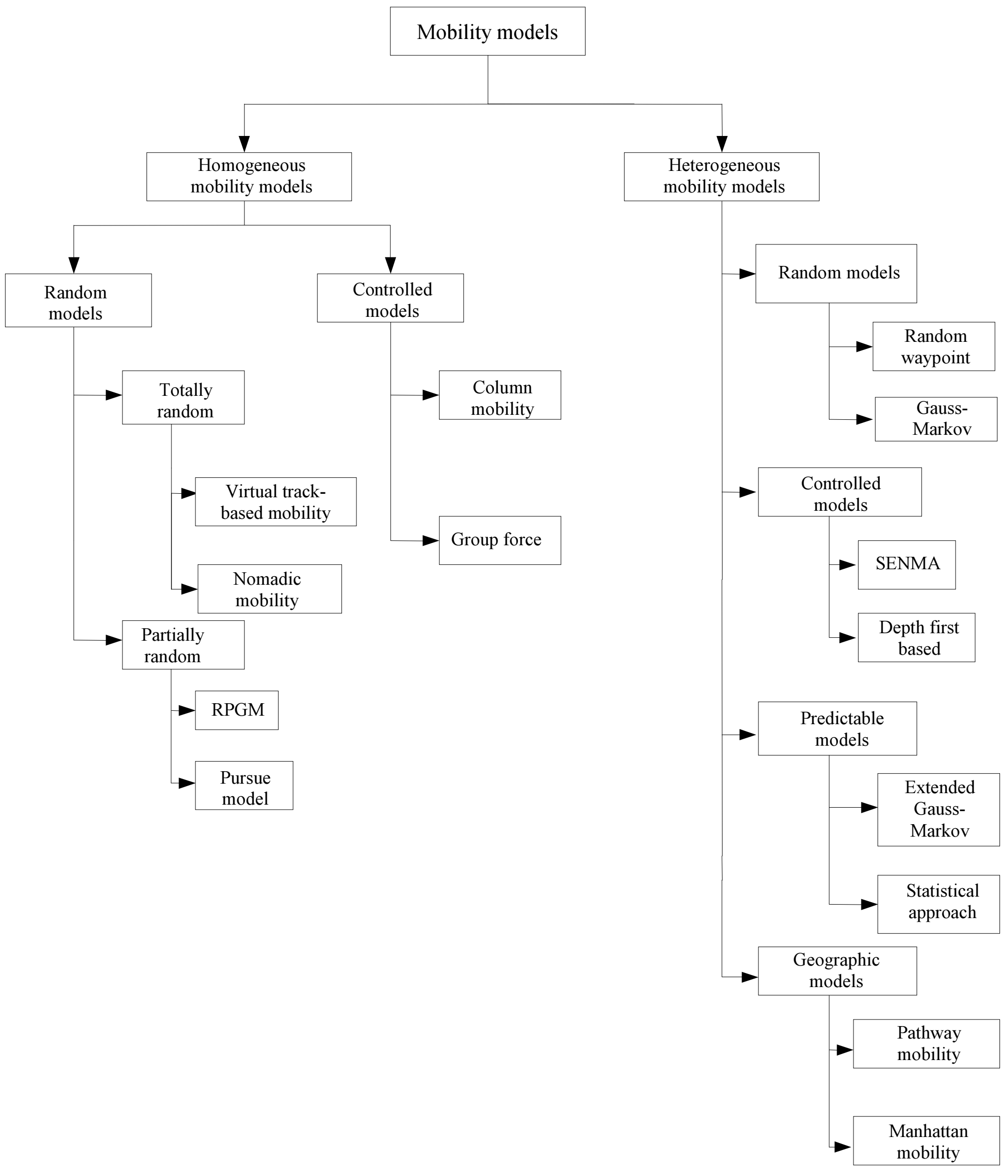

Fig. 1: Classification of Mobility Models and Examples (Bai and Helmy, 2004; Taleb *et al*., 2013)

Note that each of the previously mentioned categories can be further divided into different subcategories that are summarized in Fig. 1 which is adapted from (Bai and Helmy, 2004) and (Taleb *et al*., 2013). Say it in another way, random models, controlled models, predictable models and geographic models are four subcategories that can be derived from heterogeneous mobility models. Also, heterogeneous mobility models category contains the following categories controlled models and random models where the random models can also be divided into totally random and partially random subcategories (Taleb *et al*., 2013). Examples of mobility models that fall under each category are provided in Fig. 1 which have been slightly modified by the authors of this paper to show where the depth first mobility model fits in the adopted categorization which is adapted from (Bai and Helmy, 2004) and (Taleb *et al*., 2013).

As a result, it can be concluded that the mobility models studied in this study are heterogeneous mobility models as they are based on having a single mobile sink that collects data from static sensor nodes. To elaborate; the depth first mobility models can be classified under the controlled mobility models subcategory because, the movement of the mobile sink is restricted to calculating the movement path based on the well-known depth first traversal algorithm. On the other hand, the random waypoint mobility model and Gauss Markov mobility model can be classified under the random mobility models subcategory because in the random way point mobility the mobile sink will select random coordinates to move to. However, the movement of mobile nodes according to Gauss Markov mobility model can vary from being completely random to being completely controlled based on the values selected for the parameters that are used to select movement speed and direction, thus, Gauss Markov model can provide real life scenarios (Kartakarte *et al*., 2013; Anas and Tareq, 2014; Biomo *et al*., 2014). Therefore, we are studying the performance of WSNs under three mobility models that belong to two different categories. Since the main goal of this paper is to study the performance of WSNs under three mobility model; depth first based mobility model, random waypoint mobility model and Gauss Markov mobility model, the operation and properties of each mobility model considered in this study are discussed section 2.2. Further details regarding other mobility models are provided by (Taleb *et al*., 2013).

As routing protocols have direct impact on the performance of the WSNs, the routing protocol adopted to study the performance of selected mobility models is discussed in section 2.1. Moreover, the mobility models studied in this study are reviewed in section 2.2.

Ad Hoc on Demand Distance Vector Routing Protocol

Many research works have proposed routing protocols and algorithms that aim to improve the performance of wireless sensor networks. When route establishment method is adopted as a classification criterion, WSNs routing protocols can be classified into three category namely, proactive, reactive and hybrid routing protocols (Abdala *et al*., 2015). Figure 2 shows the three different categories and gives examples of routing protocols that fall under each category which is adapted from (Abdala *et al*., 2015).

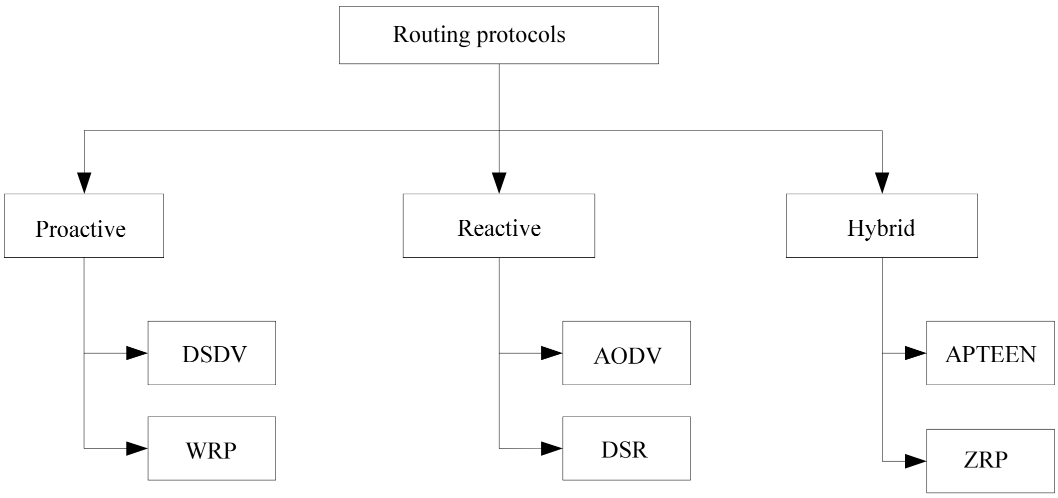

Fig. 2: Routing protocols classification and examples (Abdala *et al*., 2015)

To clarify the difference between the three categories, proactive routing protocols aim to make up to date routing information ready and available in advance even if they are not needed now. So that, these routing information are available and ready to be used instantly when they are needed. Destination Sequenced Distance Vector (DSDV) is an example of routing protocols in this category. On the contrary, reactive routing is based on creating or establishing needed routes only. As a result, routing information will not be available and ready to use, they will be established when a new path or route between two new sources and destinations is required. Ad hoc On Demand Distance Vector (AODV) routing protocol is an example on this category. Finally, hybrid routing protocols category can be thought of as a category that falls between the other two categories because, routing protocols under this category are capable of operating in proactive and reactive manners. Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol (APTEEN) is an example of protocols in this category (Liu and Kaiser, 2005; Jetindra and Dalal, 2013; Abdala *et al*., 2015)

From the research proposed in (Jetindra and Dalal, 2013), it can be concluded that DSDV is suitable for small network sizes and low movement speeds of the mobile node or nodes. On the other hand, AODV can provide efficient utilization and use of the available bandwidth which can be regarded to its reactive nature. Also, changes in network topology and route establishment can be dealt with quickly with small delay when AODV is used (Amine *et al*., 2014). Therefore, AODV is adopted as the routing protocol to be used in this study because, the work proposed in this study is based on changing the network size and varying the speed of the mobile sink. Therefore, the rest of this section will focus on explaining the operation of AODV (Amine *et al*., 2014; Ullah and Ahmad, 2009).

AODV is based on using routing tables containing one entry for each destination in the network. The reason be hid this is that AODV can make sure that the routing tables contains all the nodes in the network. Thus, each node knows every other node in the network. The second benefit is that when a node knows about other nodes in the network, AODV to avoid routing loops when new routes are required. Note that, AODV does not make routes between all nodes in the network available. On the contrary, routes are established and routing information between nodes are obtain when there is a need for them. After that, routing information will be maintain in the routing table as long as they are needed (Amine *et al*., 2014; Taneja and Kush, 2010).

When a message needs to be delivered to a specific destination, the source node first checks its routing table for available routing information regarding that destination. If routing information are available, they can be used to forward the message to the next hop which might not be the ultimate destination of the message. After that, it will be the responsibility of the new node to find the next hop node according to the correct path. This process continues and the message will go through multiple intermediate nodes until it arrives ti its destination. On the other hand, if no routing information for the destination were available at the source node, a Route Request Packet (RREQ) is built by the source node. Then, broadcasting is used by the source node in order to send the RREQ to its neighbours. After that, the neighbours of the source node will forward the RREQ packet to their neighbours too. This process continues until a route to the specified destination is found (Taneja and Kush, 2010).

In addition, AODV can initiate updates in a reactive manner. In other words, the update process in AODV is linked to the presence of events such as link failure and node movement. For example, when a node move from location to another, neighbourhood information and routing paths in the network will get affected. As a result, update process must be initiated. Therefore, route discovery will be initiated by the node that changed its position in order to update its table and find new routes. However, if the node that changed its position was an intermediate node or the destination node, then Route Error (RERR) message is created and forwarded to that node's neighbours which will forward it to their neighbours too. This process continues until RERR message reaches the source node. Consequently, the source node will start the update process so that new paths can be acquired needed (Amine *et al*., 2014; Taneja and Kush, 2010).

Thus, it can be concluded that using AODV as a routing protocol in the network have several advantages such as the ability to cope with changes in behaviour of the network, the ability to support different types of communication like unicast, multicast and broadcast. Also, the reactive nature of AODV makes it possible to establish routing paths when required with small delay. Furthermore, the update process in AODV makes it possible to repair link breakages efficiently and adapt to topological changes in a relatively quick manner without affecting the whole network because the routing tables of affected nodes only are updated needed (Amine *et al*., 2014). Therefore, AODV is the routing protocol used in this study to study the performance of three mobility models for WSNs.

Mobility Models

In this section we will discuss the three mobility models studied in this study. We will start with studying the depth first based mobility model. After that, the random waypoint mobility model is reviewed. Finally Gauss Markov mobility model is taken into consideration.

Depth First Based Mobility Model

The research work proposed in (Anas and Tareq, 2014) adopted a heterogeneous network model since their work is based on deploying a single mobile sink that is responsible for collecting data from randomly deployed static sensor nodes. Additionally, the movement of the mobile sink is controlled and calculated based on the depth first traversal algorithm of a graph. Thus, the mobile sink can start traversing the network from any node. After that the depth first algorithm is applied by the mobile sink in order to calculate and find a new position to visit. As a result, it can be concluded that the depth first based mobility model divides the movement of the mobile sink into two periods. The first period is called pause or sojourn period where the mobile sink stops moving and stays in its current period for a specific period of time. When the sojourn period expires, the movement period is started. In the movement period, the mobile sink applied the depth first algorithm in order to find a new position and starts moving towards it. In other words, in the sojourn period the mobile sink will be pausing in a vicinity of static sensor nodes that can be called the current node. Upon entering the movement period, the mobile sink will apply the depth first algorithm to select a neighbour of the current node and starts moving to the new node's position.

Gauss Markov Mobility Model

The Gauss Markov mobility model aims to represent real life scenarios by providing several parameters that can be used in order to control the degree of randomness according to which a mobile node chooses the next movement direction and speed (Kartakarte *et al*., 2013; Anas and Tareq, 2014; Biomo *et al*., 2014). According to (Liang and Haas, 1999), the movement speed and direction are selected in the initialization phase and the mobile sink will move to a specific period of time based on the selected parameters. When the current movement period is over, the pervious movement speed and direction are used in order to calculate new value for movement direction and speed. In other words, the new movement speed and direction are calculated and derived from the previous ones. To elaborate, at the beginning every node is assigned a mean value for speed and a mean value for direction. After that, the mobile sink will be moving according to these parameters for a specific period of time. When a new movement phase is initiated, the new values direction and speed are calculated again based on the values used in the previous phase and so on (Manurung *et al*., 2016).

Form the equations below, it can be observed that some parameters are used in order to restrict and control the degree of dependency that can be used to link the new calculated movement speed and direction to those used in the previous movement period. The calculations are accomplished according to the following equations provided by (Kartakarte *et al*., 2013):

$$S_n = \alpha * S_{n-1} + (1-\alpha) * S + \sqrt{1-\alpha^2} * S_{x_{n-1}}$$

And:

$$D_n = \alpha * D_{n-1} + (1-\alpha) * D + \sqrt{1-\alpha^2} * D_{x_{n-1}}$$

Note that S_n and D_n are the new movement speed and direction calculated based on the values of the same parameters in the previous interval. Also α is a parameter that is used to control the degree of dependency on the previous speed and direction of the previous interval where $0 \le \alpha \le 1$ (Kartakarte *et al*., 2013; Biomo *et al*., 2014).

According to (Kartakarte *et al*., 2013), when the value of α is equal to 0, the movement of the mobile sink will be completely random. On the contrary, the movement of the mobile node will be linear if the value of α is 1. Thus, it can be concluded that highly random mobility models can be obtained using small value of α while controlled or uniform mobility models can be achieved using large α values. Note the value of α must be greater than or equal to 0 and less than or equal to 1. Furthermore, the authors of (Wang *et al*., 2016) have studied the parameters of this mobility models and have concluded that the Gauss Markov Mobility model performs better when the value of α is between 0.4 and 0.7. Thus, this result will be taken into account when selecting the value of α for the work proposed in this study. Additionally, the next location of the mobile node is calculated according to the equations presented in (Kartakarte *et al*., 2013) and is based on the current location, movement speed and movement direction as follows:

$$X_n = X_{n-1} + S_{n-1} * \cos D_{n-1}$$

And:

$$Y_n = Y_{n-1} + S_{n-1} * \sin D_{n-1}$$

Random Waypoint Mobility Model

Random Waypoint mobility model have been used in various research works because it is one of the early models that were proposed in the area of ad hoc and sensor networks. Thus, it can be considered and a benchmark model that can be used in order to study different aspects of mobility models (Khan *et al*., 2014).

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This mobility model consists of two periods or rounds namely, pause period and motion period. When this model is applied, the mobile node enters the pause period immediately. As a result, it will stay in its current position for a specific period of time. At the end of the pause period, the movement period is start where the mobile node randomly selects a new location and starts moving towards it with a specified speed that is selected from a uniformly distributed range between [min speed, max speed]. Upon arrival to its new location, the mobile node enters the pause period again and stays in its current location until the pause period expires. After that, a new location and speed are selected in the same manner used before upon the end of the pause period (Kartakarte *et al*., 2013; Khan *et al*., 2014).

To improve the Random Waypoint mobility models, the authors in (Van, 2017) proposed an enhancement to where the new location and speed of a mobile node are not selected in a completely random fashion. Say it in another way, the new movement speed and direction are associated to those used in the previous period. Also, the mobile nodes does not have to enter the pause period after every movement period. Conversely, the mobile sink determine whether to enter a pause period depending on the probability distribution of nodes in its new location.

Performance Metrics

The performance of the mobility models presented in this study is studied according to three parameters namely, end-to-end delay, throughput and packet delivery ratio. In the following subsections these parameters are discussed and the equations according to which they are calculated are presented.

Average End-To-End Delay

According to (Amnai *et al*., 2011), end-to-end delay is the time a packet requires to arrive to its destination after leaving its source. In order to calculate the average end-to-end delay for the whole network, all packets transmitted and received between all sources and destinations pairs are averaged. Therefore, the average end-to-end delay is calculated according to the equation shown below which is adapted from (Amnai *et al*., 2011):

$$T_{AVG} = \sum_{i=1}^{N} \frac{\left(H_r^i - H_t^i\right)}{N}$$

Worth mentioning, H_r^i and H_t^i are the reception and emission instances of a packet respectively and N is the total number of received packets (Amnai *et al*., 2011). Additionally, smaller values of this metric is an indicator to a good performance of the network (Kartakarte *et al*., 2013).

Throughput

Throughput can be defined as the ratio of data packets transmitted successfully and is measured in bits/sec (Amnai *et al*., 2011). Note that, better performance is indicated by higher values of throughput. According to (Kartakarte *et al*., 2013) throughput can be calculated based of the equation shown below:

$$Throughput = \frac{Number\ of\ Packets\ Delivered * Packet\ Size * 8}{Total\ Simulation\ Time}$$

Packet Delivery Ratio

The work proposed in (Kartakarte *et al*., 2013) defined packet delivery ratio as the number of packets successfully delivered to the destination or sink node, P_{rs}, to the total number of data packets transmitted by different sensor nodes, P_{sent_i} as shown in the equation below which is adapted from (Kartakarte *et al*., 2013):

$$Packet\ Delivery\ Ratio = \frac{P_{rs}}{\sum_{i=1}^{n} P_{sent_i}}$$

where, n denotes the total number of sensor nodes in the network (Kartakarte *et al*., 2013).

Simulation Scenarios

The mobility models considered in this study were implemented and studied through simulation that was conducted using NS-2 simulator. Hence, different simulation scenarios were provided to study the performance of each mobility model. As a result, different network sizes were taken into consideration in these scenarios. In other words, the performance of the network is studied under 26, 51, 76 and 101 network sizes for every mobility model considered in the work presented in this study. Worth mentioning, for each of the network sizes mentioned above nodes are divided into two categories. The first category consists of n static sensor nodes, while the second category contains a single node that represents the mobile sink which is responsible for collecting information from the static sensor nodes. Therefore, in each scenario the total number of nodes is equal to n +1 nodes. To elaborate, if we have a network size of 26 nodes in our scenario. This will result in having 25 static sensor nodes plus 1 node that will be the mobile sink.

In addition to different network sizes, the mobile sink movement was studied under the three mobility models using different speeds. For example, for a network consisting of 26 nodes, the performance of the network is studied when the mobile sink is moving according to the depth first based mobility model with 5m/s speed. Then, in another round of simulation, the mobile sink speed is increased to 10 m/s under the same mobility model. After that, another two simulation scenarios are conducted with 15 m/s and 20 m/s using the same mobility model adopted in the previous scenarios. Consequently, the same set of simulation scenarios are conducted on the Gauss Markov mobility model and the random waypoint mobility model.

Worth mentioning the value of α used in our simulation is equal to 0.5. This value was chosen because we are studying the performance of three mobility models that belong to two different categories. In other words, the depth first mobility model is a controlled mobility model while, the random waypoint and Gauss Markov mobility models fall under the random mobility category. Since α is a parameter that is used to control the degree of dependency on the previous speed and direction of the previous interval in Gauss Markov mobility model (Kartakarte *et al*., 2013), choosing 0.5 value for α makes the Gauss Markov model act as an intermediate category between controlled mobility and random mobility. Say it in another way, it makes the Gauss Markov models partially random but at the same time cannot be counted as controlled mobility models.

Moreover, the routing protocol used in this study, AODV, was modified according to the following scenario. When a static sensor node has data to be sent to the mobile sink, it checks whether the mobile sink is its neighbour. As a result, data packets will be sent directly to the mobile sink if it is a neighbour of that sensor node. On the other hand, if the mobile sink is out of that node's vicinity, i.e. not a neighbour of the source node, the sensor node will use multi-hop communication to deliver packets to the sink node.

Note that, in the simulation scenarios conducted in this study, static sensor nodes were generating packets of 512 byte long according to the Constant Bit Rate (CBR) traffic model. Furthermore, the simulation time for all scenarios was 1000 sec and the simulation grid size was equal to 1000*1000. Additionally, for each scenario and mobility model studied in this study, the movement of the mobile sink is divided into pause periods and mobility period. Thus, the pause time of the mobile sink was equal to 5 second for all mobility models under all scenarios. Simulation parameters as shown in Table 1. Worth noting, the results obtained from each scenario are the average of ten runs for every case.

Table 1: Simulation Parameters

Parameter	Value
Simulation Time	1000 Sec
Number of Nodes	26, 51, 76, 101
Pause Time	5 Sec
Simulation Area Size	1000*1000
Traffic Type	CBR
speed	5, 10, 15, 20 m/s
α	0.5

Results

The results obtained from simulating the mobility models considered in this study are presented and discussed in this section. Worth mentioning the simulation was conducted based on the scenarios discussed in section 4. Moreover, each scenario was simulated ten times and the results obtained were the average of the ten runs for each scenario in order to obtain more accurate results.

Figure 3-5 presents the end-to-end delay values for the depth first based mobility model, Random Waypoint mobility model and Gauss Markov mobility model respectively. It can be observed that these model obtained low values for end-to-end delay when the mobile node was moving at 5 m/s speed, because at this speed static sensor nodes have enough time to send data packets directly to the mobile node before the mobile node leaves the neighbourhood of a static sensor node. On the other hand, the end-to-end delay values increased when increasing the speed of the mobile node. This can be regarded to not having enough time to send data directly from a static sensor node to the mobile sink. In other words, the mobile node will leave the vicinity of a static sensor node before that node finishes transmitting packets to it. Thus, the static sensor node is obliged to use multi-hop communication to route messages to the mobile sink which incurs higher delay. Additionally, from Fig. 3-5 it can be observed that the end-to-end delay increases when the network size is increased because longer paths are required to route packets to the mobile sink or node as multi-hop routing is used more frequently. As a result, packet will suffer from higher values of end-to-end delay.

From Fig. 3-5, it can be concluded that for all cases i.e., different network sizes and different speeds of the mobile sink, the performance of the depth first based mobility model was better than the other two models since lower values of end-to-end delay were obtained under different scenarios by this model.

The simulation results in term of throughput are shown in Fig. 6-8. It can be observed that the depth first based mobility model and the random waypoint mobility model, Fig. 6 and 7, obtained better results in terms of throughput when the mobile sink was moving at a speed of 10 m/s. The reason behind such result can be regarded to the use of multi-hop routing to deliver packets. Say it in another way, when the mobile sink is moving at 10 m/s speed, it will leave the vicinity of static sensor nodes quickly. Hence, the static sensor nodes will not have enough time to use single-hop communication in order to deliver packets directly to the mobile sink. Therefore, the static sensor nodes will use multi-hop communication to route packets to the sink node which will increase the delay. However, increasing the delay packets suffers from will be beneficial to the mobile node as it will not suffer from buffer overflow situation which may occur when the mobile sink is in the vicinity of multiple static sensor nodes and all these nodes use single-hop communication to delivery messages directly to the mobile sink.

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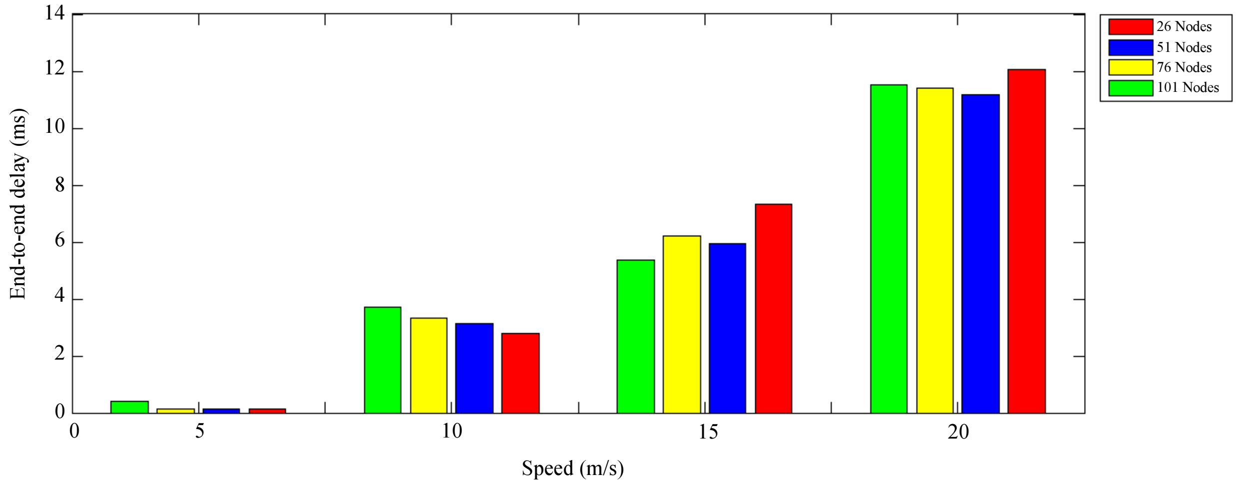

Fig. 3: Depth first based mobility model end-to-end delay

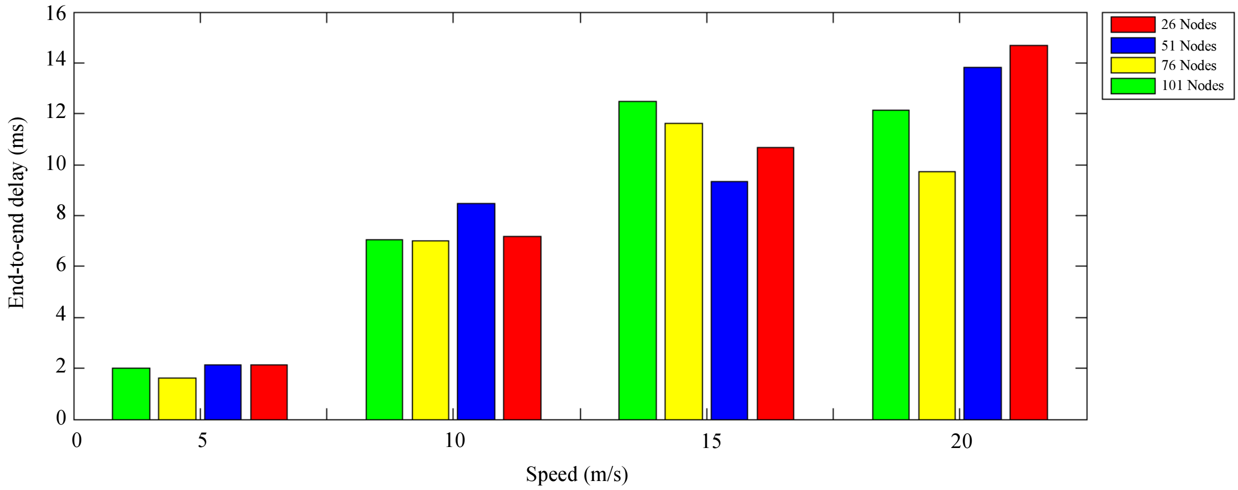

Fig. 4: Random waypoint mobility model end-to-end delay

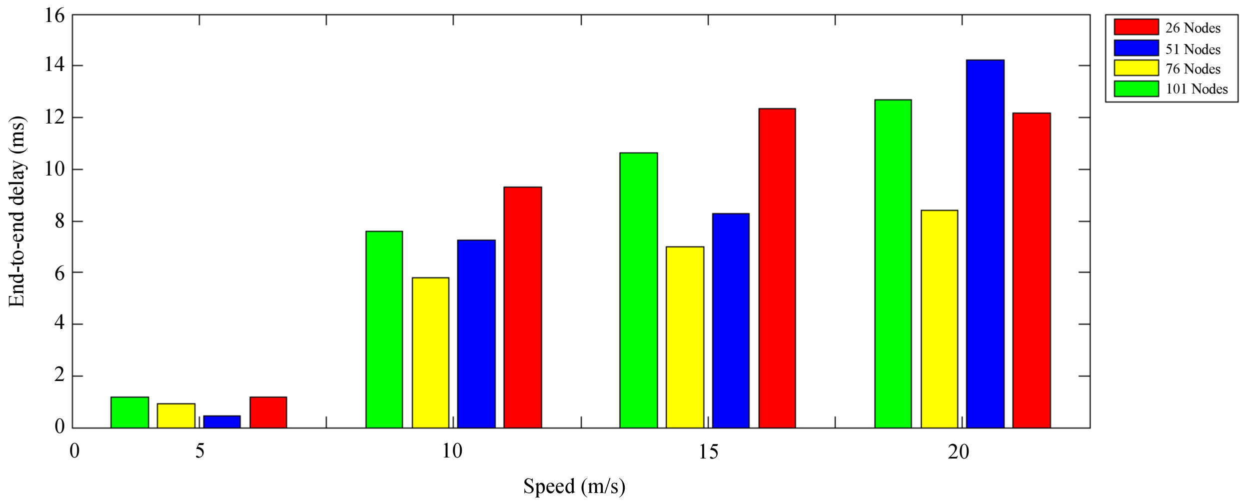

Fig. 5: Gauss Markov mobility model end-to-end delay

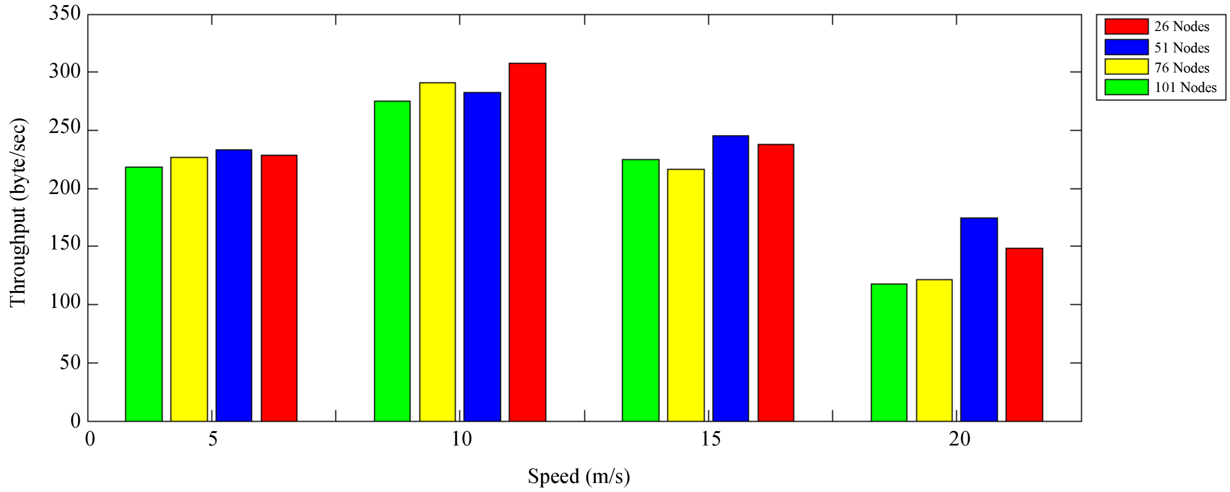

Fig. 6: Depth first based mobility model throughput

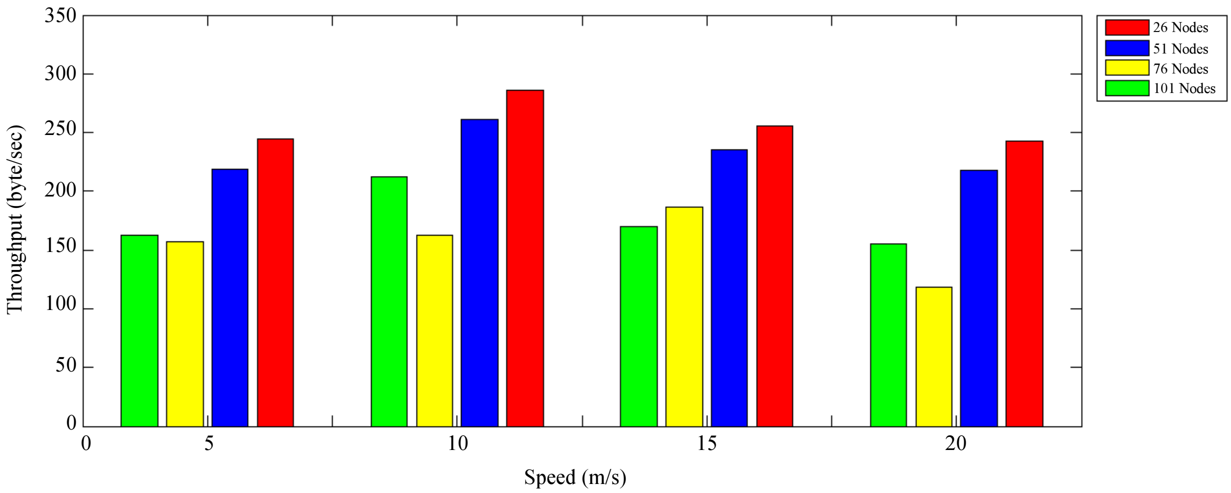

Fig. 7: Random waypoint mobility model throughput

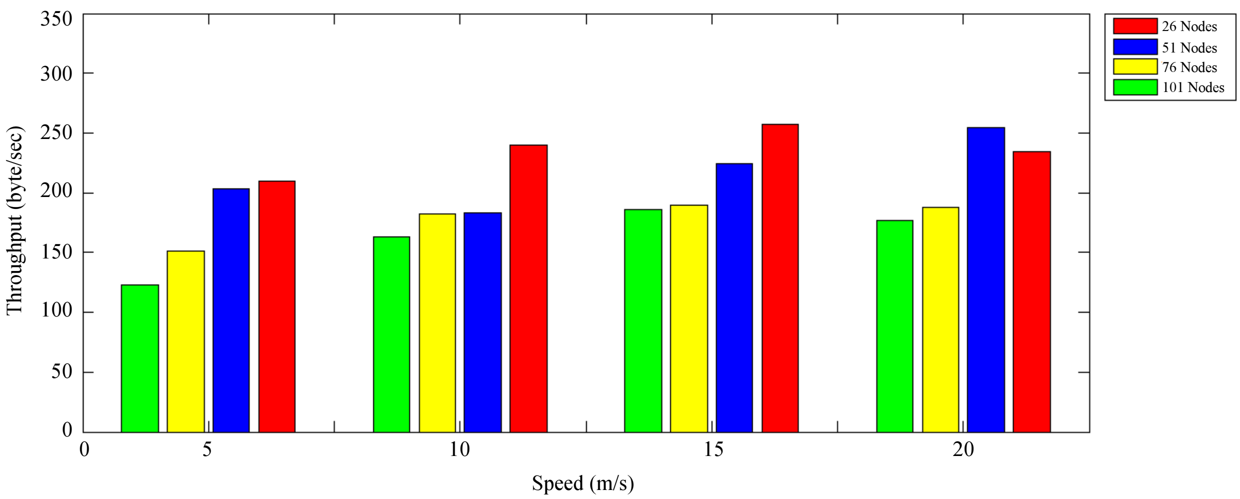

Fig. 8: Gauss Markov mobility model throughput

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However, the performance of Gauss Markov mobility model, Fig. 6, was better when the movement speed of the mobile sink was equal to 15 m/s. this can be regarded to the properties of this mobility model. As explained in section 2.2.2, the mobility pattern of the mobile node is divided into phases where in each phase new values of a movement speed and direction are calculated based on the old values of the same parameters that were used in the previous phase or time interval. Since the new direction of the mobile node is based on its old direction, this may result in some static sensor nodes being rarely or not visited by the mobile sink. As a result, these rarely visited nodes will be relying on multi-hip communication rather than using single-hop communication. When, the mobile sink was moving at a speed of 15 m/s, throughput values increased because the mobile sink will move closer to these nodes more frequently. Consequently, shorter paths are needed to route packets to the mobile sink.

Furthermore, Fig. 6-8 show that the performance in terms of throughput was better for networks consisting of 26 and 51 nodes because these network sizes are considered to be small and medium size networks. Thus, the paths required to route packets are shorter than those needed in 76 and 101 nodes networks. Consequently, packets will suffer from low delay values to reach their destinations which results in better values for throughput.

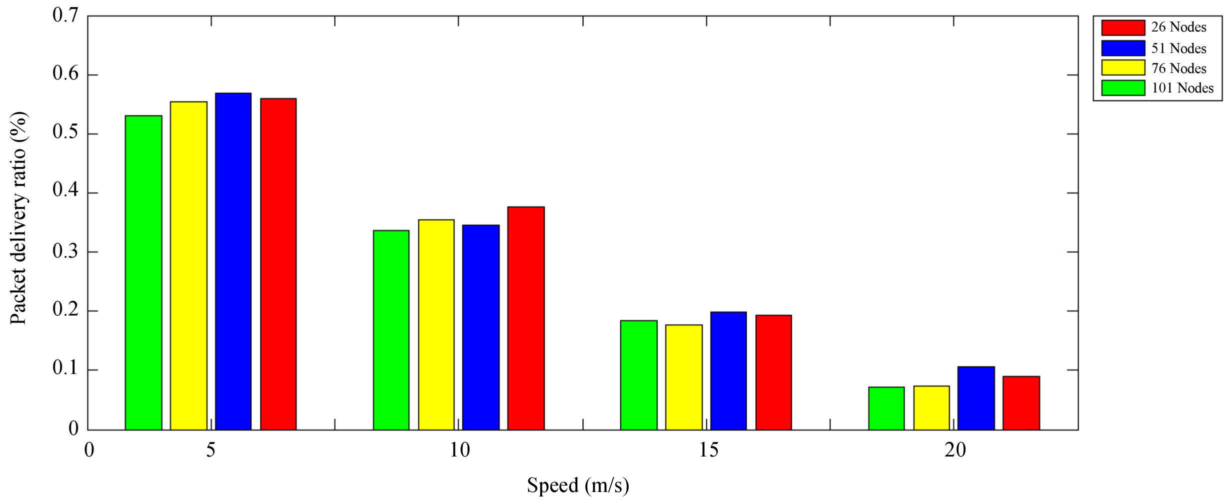

Fig. 9: Depth first based mobility model packet delivery ratio

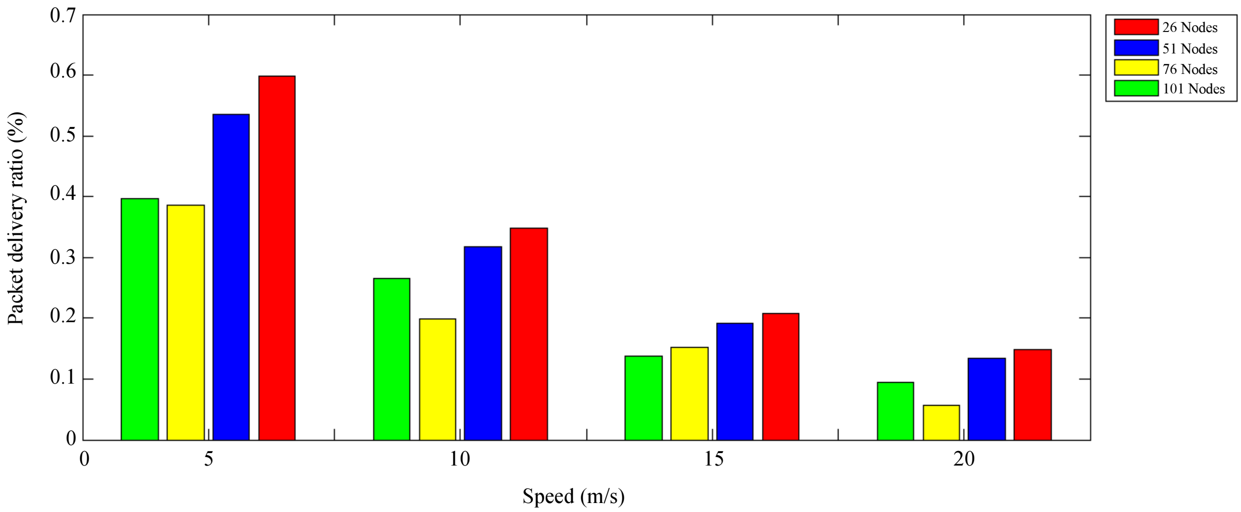

Fig. 10: Random waypoint mobility model packet delivery ratio

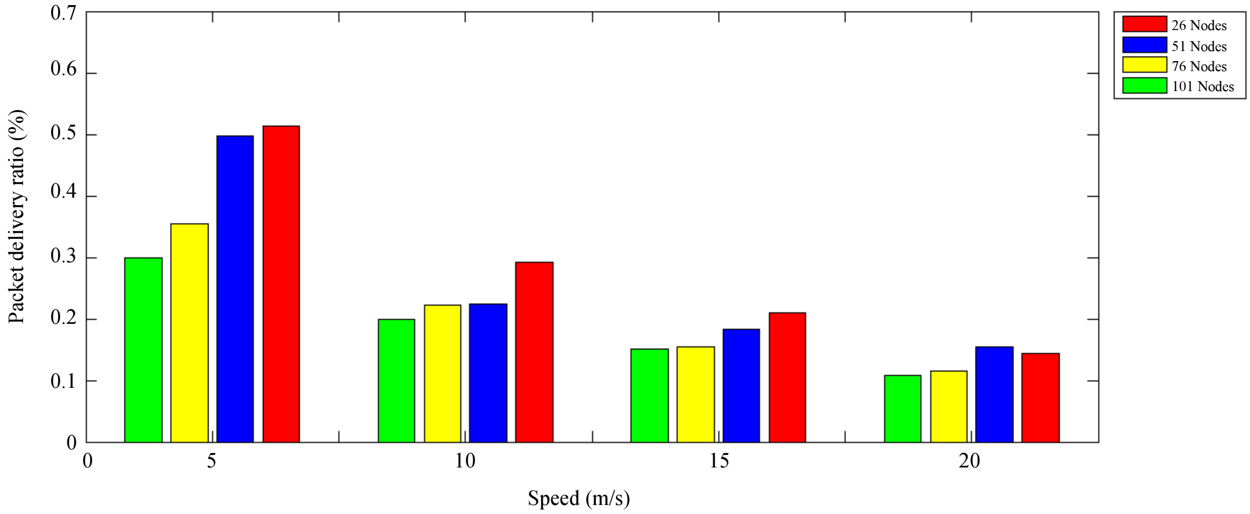

Fig. 11: Gauss Markov mobility model packet delivery ratio

The simulation results obtained regarding packet delivery ratio are presented in Fig. 9-11. The figures and the obtained results show that three mobility models studied in this study achieved better performance in terms of packet delivery ratio when the mobile sink was moving at a speed equal to 5 m/s. This can be regarded to low values of end-to-end delay obtained in Fig. 3-5. In other words, since static sensor nodes are combining the use of single-hop and multi-hop routing depending on whether the mobile sink is in a node's vicinity, packets will suffer from low delay values until arriving to the mobile sink. Moreover, the mobile sink is moving at a reasonable speed which will give static sensor node enough time to finish transmitting packets directly to the mobile sink. Furthermore, it can be observed that networks consisting of 26 and 51 nodes achieved better performance than networks consisting of 76 and 101 nodes, because shorter paths are needed to route packets when using 26 and 51 nodes network sizes. Moreover, for networks consisting of 26 and 51 nodes, the frequency according to which static sensor nodes are visited by the mobile sink is higher than that achieved when using networks consisting of 76 and 101 nodes. Thus, single-hop communication can be used to deliver packets to the mobile sink which results in increased or better values pf packet delivery ratio.

Conclusion and Future Work

In this study, the performance of three mobility models for wireless sensor networks was studied using NS-2 simulator under different simulation scenarios. Also, different metrics, namely, end-to-end delay, throughput and packet delivery ratio, were used to investigate how these mobility models behave under different network sizes and speeds of the mobile sink. Furthermore, AODV routing protocol was used to route packets from static sensor nodes to the mobile sink. Our results show that the three mobility models studied in this study performed better for networks consisting of 26 and 51 nodes. Also, it can be concluded that for 26 and 51 nodes networks the performance of the depth first base mobility model was better than the performance of the other two mobility models studied in this study. As a result, it can be concluded that the depth first mobility model is suitable to be use for small and medium sized networks as it performed better that the other two mobility models and achieved around 58% packet delivery ratio when the mobile sink movement speed was 5 m/s. Furthermore, the depth first based mobility model acquired the highest throughput, around 230 bytes/sec, under the same speed of the mobile sink. Finally, it can be observed that the results obtained by the depth first mobility model regarding End-to-End delay were much better that the other two mobility models for all cases and especially when the speed of the mobile sink was equal to 5m/s. Thus, it can be concluded that the depth first based mobility model can be used when having small or medium size network and when the mobile sink movement speed is low.

For future work, we plan to study the performance of the three mobility models, namely depth first based mobility model, random waypoint mobility model and Gauss Markov mobility model, in terms of energy consumption. In other words, the effect of these mobility models on energy consumption of static sensor nodes and the mobile sink will be taken into account. Moreover, we intended to study the behaviour of the same mobility models under different packet sizes. Additionally, we plan to study how the mobility models studied in this study will perform under different routing protocols in addition to AODV. Also, the performance of Gaus-Markov mobility model can be studied under different values of dependencies. Finally, we plan to include other mobility models and study their performance using the same approach adopted in this study.

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Ethics

This research manuscript is original and has not been published elsewhere. The corresponding author confirms that all of the other authors have read and approved the manuscript and there are no ethical issues involved.

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