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MQRP: Mobile Sinks-based QoS-aware Data Gathering Protocol for Wireless Sensor Networks-based Smart Grid Applications in the Context of Industry 4.0-based on Internet of Things

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Abstract: The recent advances in internet of things (IoT) and industrial wireless sensor networks (IWSNs) paradigm provide a promising opportunity for upgrading today's elderly electricity industrial systems and even allow the fourth stage of the industrial revolution, referred to as smart grid industry (SGI) 4.0. In SGI 4.0 paradigm, the WSNs are considered as promising solutions due to their advantages, such as cable replacement, ease of deployment, flexibility, and cost reduction. However, harsh and complex smart grid (SG) environments pose great challenges to guarantee reliable communication for WSNs-based SG applications due to equipment noise, electromagnetic interference, multipath effects and fading in SG environments. This results in deteriorating the quality-of-service (QoS) requirements as well as the network lifetime of multi-hop communication-based WSNs for SG applications. Thus, for SGI 4.0 paradigm to come true, a WSN-based highly reliable communication infrastructure is crucial that will wirelessly connect and integrate power system components for more efficient, reliable, and intelligent operations of the next-generation electricity power grids. To address these challenges, in this paper a novel multi-mobile sinks-based QoS-aware data gathering protocol (called MQRP) for WSNs-based SG applications has been proposed to empower SGI 4.0. The extensive simulations study is carried through a network simulation tool called EstiNet9.0. The obtained experimental facts show that the proposed scheme has not only improved the QoS performance metrics, such as packet delivery ratio, memory utilization, control message overhead, residual energy, network lifetime, and throughput, but also reduced packet error rate and end-to-end delay compared to existing data collection schemes.

Keywords: Internet of things, Industry 4.0, Smart grid industry 4.0, Smart grid, Wireless sensor networks, Mobile sink, Routing protocol.

1. Introduction

Recently, with the rapid development of IoT and services to manufacturing, the fourth stage of the digital industrial technology revolution, namely, Industry 4.0, is believed to be approaching [1]. Industry 4.0, is a rapidly growing field and gaining significant attention from researchers, manufacturers, and application developers in various domains, such as industrial automation and manufacturing [2]. The vision of Industry 4.0 is to make the factories smart enough by connecting and integrating all unconnected physical objects of the traditional factory world through a network for enabling adaptability, flexibility, and efficiency in supply and demand processes between the factories [3]. These industrial upgrades will enable fast, more flexible, and more efficient processes to increase efficiency and productivity of higher-quality goods at low costs. Industry 4.0 will not only make the traditional industry even more immersive and pervasive, but also modify the profile of the workforce ultimately changing the competitiveness of companies and regions worldwide to improve people's lives [4, 5].

In Industry 4.0, the wired or wirelessly connected systems that are physically placed in distant geographical locations and across different industries can interact with one another using standard Internet-based protocols and analyze data to predict failure, configure themselves, and adapt to changes. This machine-to-machine communication between systems located in different remote places resulting in intranet or internet of things [6]. Currently, most devices within factories are connected based on wired infrastructure working over industrial protocols to streamline management operations due to dynamic reconfigurable industry elements [7]. However, the wireless solutions are increasingly playing a complimentary role to wired solutions for strengthening management and control capabilities of the industry elements. In this regard, IWSNs are an invaluable technology for realizing the vision of Industry 4.0, due to their low cost identifying, sensing, networking, and processing capabilities [8]. The IWSNs provide a virtual layer where the information about the physical factory world can be accessed by any computational system/user placed in a remote location to accomplish some objectives [9]. The main attributes of IWSNs-based networks are to enable smart production reliability and to increase economic benefits with least breakdowns and maintenance cost in a bounded time interval in harsh industrial environments. With these objectives, IWSNs have proved their importance in a wide range of industrial applications, such as healthcare systems, transportation, modern agriculture, steel mills, offshore drilling, underwater applications, oil and gas industry, area surveillance, and several others [10-14].

In the context of SGI 4.0-based on IoT, the performance of QoS-aware multi-hop cooperative communication protocols depend on several performance metrics, including latency, throughput, reliability, mobility, scalability, lifetime, coverage [15, 16, 22]. In SGI 4.0, WSNs integrate the electric power industrial components to the information world through IoT, which leads to innovative services and efficient productivity [17]. Thus, WSNs can significantly improve product quality, speed up production, make installation easier, increase the flexibility and reduce expenditure for the infrastructure in the SGI 4.0 [18]. In SGI 4.0, the existing and envisioned applications of WSNs cover a wide range, such as energy management, dynamic pricing, demand response, dynamic pricing, outage management, distribution automation, distribution automation, substation automation, load control, advanced metering infrastructure and overhead transmission line monitoring, and several others [19, 20]. The diverse QoS requirements of these applications are presented in Table.1. Importantly, all these applications would lead to new products, processes, and services that will provide a competitive edge for in the fourth generation global marketplace. Concurrently, it would also improve the day-to-day lives of ordinary citizens by ensuring the reliability of the electric power infrastructure with the minimal human intervention [21]. However, the currently designed and envisaged smart grid applications realization directly depends on reliable and efficient communication capabilities of the deployed network.

Recent field tests reveal that the wireless channels in power grid have many unique challenges due to equipment noise, electromagnetic interference, fading and multipath effects [20, 22]. This leads to time and location dependent link quality variations of wireless links, which makes challenging to guarantee QoS-aware data transmissions in multi-hop communication-based WSNs for SG applications [19]. Thus, the key design issue is to provide link quality aware data delivery under adverse wireless communications conditions to accomplish QoS requirements, such as latency, throughput, reliability, mobility, scalability as well as network lifetime in harsh SG environments [23]. To address these challenges, in this paper we propose a novel multi-mobile sinks-based QoS-aware data gathering protocol for WSNs-based SG applications to empower SGI 4.0. The main contributions of this study are listed in the following section.

1.1 Contributions

In this paper, we propose a multi-mobile sinks-based QoS-aware data gathering protocol and formulate the problem as mixed integer linear programming (MILP) for SG applications. The developed scheme follows a hybrid mobility pattern, where initially sinks move in a strictly deterministic manner and then based on self-learning, that attempts to significantly improve region-based coverage issues, avoids nodes buffer overflow time and reduce latency by scheduling the mobile sinks movement in the network. Moreover, the designed scheme also considers aggressive data collection strategy by enabling multi-hop data collection for the sensor nodes away from the mobile sinks. It effectively reduces long distance data transmission energy consumption in a greedy manner for SG applications in the network. The designed scheme during multi-hop data forwarding process preserves high link quality among sensor nodes as well as to the mobile sinks for minimizing corrupted/invalid and data packet loss in the network. In addition, the designed scheme by using a combination of mobile sinks distributes data traffic and energy consumption load evenly with lower bounded latency in a greedy manner for SG applications. In sum, the designed scheme cuts down total energy consumption under the condition that the total amount of QoS data collected by the evenly distributed mobile sinks is maximized in the smart grid environments. In the end, we conducted simulation experiments using a network simulation tool called EstiNet9.0. The obtained results from the simulations study validate the effectiveness of the proposed scheme in terms of packet delivery ratio, packet error rate, latency, throughput, memory utilization, control message overhead, and energy efficiency.

(Table.1)

1.2 Paper organization

The rest of the paper is organized into five sections as follows: The following Section 2 discusses the existing routing schemes in the smart grid. The problem statement and research motivation are described in Section 3. In Section 4, we discuss network model and proposed a scheme for smart grid applications. The path loss and simulation model are discussed in Section 5. Section 6 gives an analysis based on simulation results of the proposed scheme. In the last Section 7, we conclude the paper and outline some directions for future work.

2. Literature Review

WSNs due to their high practical significance are the key technology enabling the deployment of SGI 4.0. Prior to the SGI 4.0, a few advanced energy efficient and QoS-aware manufacturing schemes for WSNs-based SG applications have been proposed. Some of them mainly focus on increasing the lifetime using various techniques at different levels for energy efficient data transmission in the smart grid. For example, in [24], the authors developed a multi-layer-based routing mechanism to improve the nodes residual energy for efficient packet delivery in the smart grid. The study in [25], focus on designing a distributed routing mechanism that provides energy efficiency at the data transmission level in the smart grid. The work in [26] mainly focuses on level based multicast routing tree for minimizing long distance communication and latency for reliable data transmission in the smart grid. The authors in [27] studied a routing algorithm that considers the data size and transmission rate for energy efficient reliable communication in the smart grid.

Some other approaches aim to minimize the data packet collision, packet error rate and latency for efficient packet delivery in the smart grid. For instance, the authors in [28] propose a data traffic-aware routing mechanism that is capable of overcoming a false indication caused by temporary loss of data, signal interference, or invalid data to reliable data transmission in the smart grid. Rui *et al.* in [29] attempt to solve data packet collision and data redundancy issues in hostile smart grid environments. The authors in [30] studied the optimal sensor computational overhead mechanism for estimating the multi-hop architecture-based communication delay and packet errors in the smart grid. The work in [31] focuses on a centralized data collection method in which sink node divides a tree into several branches with the aim to minimize latency and data packet collision, and to increase throughput in the smart grid. The work in [32] mainly focuses on quality aware routing for improving the packet delivery ratio, latency and throughput with least overhead and energy consumption cost. Although some novel spectrum-aware communication frameworks have been proposed in [22, 33] provide valuable insights and guide design decisions for WSN-based SG applications, however, the management overhead and implementation complexity of these schemes are very high. In addition to abovementioned studies, some novel mobile sink-based data collection schemes for WSNs have been proposed in [34-36]. However, these schemes cannot be directly implemented in hostile smart grid environments without modifying the protocol stacks at various levels.

3. Problem Statement and Motivation

The common goal of the existing studies is to provide energy efficient and link quality-aware reliable multi-hop data transmission in WSNs-based smart grid applications (See section-2 for details). However, most of them are not fully adequate to utilize the node limited energy efficiency due to lack of an appropriate transmission control mechanism in the smart grid environments. Moreover, they generally ignore the impact of multipath effects and interference on transmission reliability in harsh nature SG environments. Therefore, in most of the deployment scenarios, a huge amount of corrupted and redundant data packets are generated results in additional control message overhead, which also consumes a significant of nodes energy in the network. In addition, most of them claim that observed information always moves over a set of shortest minimum spanning tree or chain like paths in a multi-hop manner to reduce latency from data sources towards the sinks. However, due to relaying data over a large number of hops on the selected shortest paths consume available resources more rapidly than others nodes in the network and thus leading to earlier nodes death. Also, the nodes one hop or two hops near to the static sink may run out of energy than others since all network traffic is funneled through these nodes in the smart grid. This phenomenon creates network a partitioning, hotspot problem and coverage issues and thus degrades the overall performance of the schemes in terms of reliability, latency and throughput in harsh nature SG environments. In sum, the existing communication solutions based on static sink are not resilient or efficient to provide energy efficient and QoS-aware real time reliable communication in the smart grid. Therefore, for a reliable fourth generation smart grid paradigm to come true, an intelligent, accurate, robust monitoring and real-time diagnosis WSNs-based communication framework is essential.

In this respect, gathering and relaying data using mobile sinks could be a promising solution for improving QoS requirements as well as prolonging the lifetime of WSNs in SG [37, 38]. Using a mobile sink, the probability of transmission error, collisions, latency, hotspot, bottleneck and attempts to compromise sensor nodes in order to overhear the collected data can be reduced as an excessive number of relaying hops during conveying information are avoided in the network. Moreover, the battery lifetime, throughput and data fidelity of individual sensors can be improved by shifting the energy consumption and communication burden to mobile sinks. In addition, the control center is capable of collecting all the available data from sensor nodes efficiently by traveling the sinks in sparse and even in disconnected or partitioned network areas [39].

Generally, in large-scale network deployment, some sensors need to be visited more frequently than others, since the data generation rates based on the event occurrence frequency in sensors may vary in different locations in the smart grid. In this scenario, the use of a single mobile sink data collector for visiting the transmission ranges of all sensors before their buffers overflow may not be efficient enough in the smart grid [40]. Moreover, it would incur long latency in data gathering, which may not meet the strict latency requirements of various smart grid applications. A possible solution to this problem is the deployment of multi-mobile sinks for data gathering in the smart grid at different locations. This will reduce the length of each tour and provide high predictability in inter-visit durations, which ultimately prevents data loss and fulfill latency requirements for WSNs-based SG applications. This motivates us for designing a novel communication paradigm for WSN-based smart grid applications to empower SGI 4.0. However, visiting the network area in an efficient and timely manner with satisfying converge is challenging for mobile collectors to meet QoS requirements of WSN-based applications in harsh nature smart grid environments. Realizing the facts, in this paper we propose a novel multi-mobile sinks-based QoS-aware data gathering protocol for WSNs-based SG applications to empower SGI 4.0. The extensive simulation results show that the proposed performs well and has not only improved the QoS performance metrics, such as packet delivery ratio, memory utilization, control message overhead, residual energy, network lifetime, and throughput but also reduced packet error rate and end-to-end delay compared to existing routing schemes.

4. Proposed Scheme

The entire routing mechanism of our proposed scheme has been divided into the following sections.

4.1 Network Model and Assumptions

The network model of our proposed scheme is shown in Fig.1. In this model, the entire network is divided into three basic layers, namely, lower, middle and upper layer also called application layer. These lower, middle and upper layers consist of sensor nodes, mobile sinks, and a base station as well as a user/s, respectively. In the lower layer, the sensor nodes are distributed in a 500kV outdoor grid station, aim to acquire, collect and may process the event data from the geographically distributed power grid systems over a large area. These tiny devices collaboratively monitor the state of power grid systems and store the most recent information in their limited buffers. In the lower layer, the location of the sensors is one of the most critical factors related to the event coverage, since the area coverage problem is closely associated with the performance of WSNs deployed for SG applications. In a large sensing field, the total event area-coverage initially provided by the sensors in random deployment cannot be guaranteed at full coverage, as in the deterministic deployment, due to harsh nature of SG environments. Due to its stochastic nature, it might result in accumulation of sensors in some areas and no node or very few nodes in other areas, therefore this is not a preferable solution in this scenario. Consequently, to obtain acceptable event coverage, sensor nodes are deployed deterministically in the smart grid.

In the middle layer, the mobile sinks aim to interact, collect and successfully transfer data over long distance wirelessly to neighboring mobile sinks or directly to a base station (BS). This middle layer acts as an interface between the sensors and remote users connected to a BS. A mobile sink is a lightweight ground vehicle equipped with sophisticated rechargeable batteries, which can easily be recharged periodically at the base station, moves around predefined large geographic areas. Moreover, it is equipped with powerful hardware units capable of long distance communication and processing capability compared to sensor nodes in the network. For mobile sinks' movement, railroad like virtual infrastructure is adopted, which are placed in different locations of the network by a predefined strategy as shown in Fig. 1.

The core of the application layer is to provide data processing and services for remote users. The received data from the BS is controlled by related management systems and then various services will be provided to all kinds of remote users. The base station is a powerful trusted device that is responsible for providing unlimited power and highly stable internet connectivity to remote users at the upper layer. Since this layer is the basis of IoT, the long-range wireless, and wired communication technologies are important in this layer to monitor the data anywhere in the world.

In our proposed scheme, we consider several assumptions listed as follows: First, all deployed static sensor nodes have limited buffer size and possess limited energy replenishment capabilities. Second, each sensor node captures the events in its surroundings and records them in its buffer. When a mobile sink visits a sensor node, it transfers sensor data to its own unlimited large data storage until the sensor's memory is freed. Third, the superfluous energy spent for the operations and movement of the mobile sinks do not affect sensor network lifetime in the smart grid. Fourth, each sensor node and mobile sink know its own and neighbor nodes position which can be obtained through the use of GPS or a localization scheme presented in [41]. Fifth, the actual data transfer time between sensor nodes and from the sensor node to a sink is negligible compared to the delay due to sink movement. Sixth, the wireless channels for mobile sinks are bi-directional and asymmetric like sensors, however, have a high data rate connection as well as the communication range to each other and to the BS, which is connected to the internet through any other wired or wireless network. Moreover, it is assumed that data transmission does not incur any loss between the mobile sinks and a BS, and latency is negligible. In addition, we assumed that the queuing discipline is First Come - First Serve (FCFS), which means the data that is generated first is picked up first. At the end, we assumed Carrier Sense Multiple Access (CSMA) mechanism to avoid packet collision in the network.

(Figure 1)

4.2 Multi-mobile Sinks-based QoS-aware Data Gathering Protocol (MQRP)

4.2.1 Network initialization

At the beginning, we first divide the entire sensor network into several subnetworks based on sensors geographical locations in the smart grid. Then, we compute a minimum cost tour for each mobile sink by solving the Traveling Salesman Problem (TSP), that decides the path to visit each sensor node exactly once in geographically distributed subnetworks. At the end, the schedules for subnetworks are concatenated to form an entire schedule of the network. In smart grid, each deployed mobile sink needs to explore its sensing field by following the user instructions received from a BS. While exploring, each mobile sink broadcasts network initialization messages (ini_msg) periodically in its range to inform sensor nodes about its current location and unique identity across the network. Upon receipt of the "ini_msg" from the mobile sink, each sensor node that can decode the message correctly broadcasts information sharing message ($info\_msg$) to discover their one-hop neighboring nodes in each subarea in the network. Then, each receiving sensor node that can decode an information sharing message correctly replies via acknowledgement message (ack_msg) to the sender node, which ensures that the message has been received successfully at the receiver. Herein, each sensor node uses restricted rebroadcasting of the received message, which is limited to its one hop neighboring nodes so that sensor nodes out of the communication range of a mobile sink can receive it in the subnetwork. The main fields of the information sharing message are: sensor node unique identity, distance information to the neighboring sensors and a sink/s, residual energy and location information. During this process, each mobile sink and sensor node deployed in the smart grid is responsible to update entire information in its routing table as shown in the Fig. 2.

Lately, the sensor nodes that are one hop away from the mobile sink reply via reply message (rep_msg) message. The sensor nodes that are in communication range of a mobile sink, however, are far reply via short distance based multi-hop forwarding technique in the network. The main fields of the reply message are: sensor node unique identity, distance information, residual energy, location information and hop distance to the corresponding intermediate node receiving the initialization message. In our scenario, it may also be possible that a sensor node chooses more than one mobile sinks as its final destination in a subnetwork. The hop distance value for the nodes that are a single hop away from the sink is 0, however, increases iteratively by 1 as the number of hops increases (maximum set to 3) to the corresponding intermediate node in the network. For those sensor nodes that are connected to multiple mobile sinks, they can send their "rep_msg" to both mobile sinks using FCFS (First-come, First-served) mechanism. Upon receiving the "rep_msg" messages from the sensor nodes, a mobile sink marks the current location and other necessary information as mentioned above of each sensor node in its routing table. In addition, deployed sinks also periodically update each other by sending sink information message ($sink\_msg$). The main fields of the sink information message are: mobile sink unique identity, residual energy, sink location information, distance information of each other as well as to the BS. In the designed scheme, each mobile sink is responsible to construct its distinct routing table to store information about its neighboring mobile sinks in the network. Consequently, a mobile sink sends an acknowledgement message to its each associated member sensor node as well as neighboring mobile sinks in the network. Thus, all wireless links between sensor nodes, mobile sinks and mobile sinks to the base station are bi-directionally tested in the network. The entire process follows CSMA mechanism to avoid packet collision in the network.

(Figure 2)

4.2.2 QoS-aware data gathering using mobile sinks

Recently, QoS-aware data collection using mobile sinks via short-range communications has emerged as an active area of research due to the increasing popularity of real-time smart grid applications to empower SGI 4.0. Generally, the amount and frequency of sensor data generated in different power grid areas expected to be higher and vary based on the event occurrence frequency, which is generally a function of the sensor nodes location. Therefore, buffer overflow time of different sensor nodes located at different places may not be the same in the networks. To this end, a node with higher data generation rates may be visited multiple times before another one with a lower data generation rate is visited in the networks. However, the round-trip time consumption of the longest data gathering tour to visit a node that generates data at higher rates must not exceed the time constraint for filing the memory of the sensors to avoid buffer overflow in the network. Thus, the buffer size of sensors and the latency of data collection latency are highly affected by the mobile sinks movement schedules. Therefore, it is important to keep a low average data latency by taking into account the vicinity where the possibility of an event detected by the sensor nodes is higher.

Currently, there is two delay tolerance buffering strategies, namely, subflow-based and queue-based have been used in this study. The subflow-based and queue-based techniques allow buffering of only self-generated data and any data traffic coming from the neighboring sensor nodes at a node in the network, respectively. The combination of the both techniques naturally leads to the best lifetime and delay-tolerance performance of the sensor nodes in a certain area that generates data at higher rates and in other areas where sensor nodes generate data at low rates in the network. However, the sensor nodes, one hop away from the mobile sinks are not allowed to buffer the relay traffic from other sensor nodes. Consequently, as soon as a sensor node one hop away from the mobile sinks receives the data from other sensor nodes, it immediately forwards the data to its associated mobile sink in the proposed scheme to fulfill the latency requirements of various SG applications.

In addition, to reduce latency, random, predictable and controlled mobility patterns are three different techniques that a mobile sink must follow for data gathering from the sensor nodes in the smart grid. In random mobility pattern, the mobile sink movement is done in an arbitrary fashion considering the speed and position of the movement in the network. The key advantage of this technique is the easier implementation due to its simplicity. However, due to lack of the future location predictability of the mobile sinks, it may result in excessive data packet loss in the network. Moreover, due to long latency requirements, it may also not be efficient for large-scale WSNs-based smart grid applications. In predictable mobility pattern, the mobile sinks move in a certain pattern along a certain trajectory that could be periodic movements in the smart grid. The key feature of this technique is the predictability of the future positions of the mobile sinks in the network. In addition, sensor nodes can also predict the sinks arrival time with some precision based on the previous history in their locality for optimizing the sensing and data collection process in the network. In controlled mobility pattern, a mobile sink in order to achieve better results can change its trajectory and movement speed in a deterministic way. The main characteristics of this pattern are robustness and simplest possible movement in the network. Moreover, this movement pattern guarantees to visit all sensor nodes in a distinct terrain and thus collecting data even from disconnected areas of few sensors in the network. In addition, this movement pattern assures specific conditions, for example, visiting some sensors within a pre-defined time even under the presence of some obstacles. However, the main drawback of controlled mobility technique is its unpredictable movement pattern of a mobile sink in the network. The selection of one of these mobility patterns for a mobile sink may yield diverse delay tolerance network performance in the network. These mobility patterns result depending on the application scenario, network size and certain environmental conditions in the smart grid. Herein, we use a hybrid mobility pattern consists of predictable and controlled mobility to achieve superior network performance due to their several aforesaid advantages.

In the proposed scheme, sensor nodes hold sensed data in their buffer by taking into account subflow-based and queue-based techniques and then wait for a mobile sink to come near them to send sensed data to it. Thus, data is collected in a passive manner in the network. Note that, only the relay nodes follow both subflow-based and queue-based mechanism to store data in their buffers in the network while the other nodes just simply follow subflow-based data buffering mechanism in the entire network. Herein, each mobile sink is responsible for gathering data by visiting the transmission range of local sensor nodes in an assigned subnetwork in the smart grid. Thus, a set of mobile sinks roams over predefined sensing fields along the fixed paths to collect data from sensors via short-range communications in the entire network. In this way, maximum energy saving at each sensor node is achieved in the field. However, the sensor nodes far from the sink may need to spend an excessive amount of energy due to long distance based data transmissions in the network. In addition, the low velocity of the mobile sinks in some regions would result in long data gathering latency, which may not satisfy the latency requirements of the various time-sensitive WSN-based smart grid applications. In this respect, a multi-hop data transmission mechanism can save maximum energy at each sensor node and avoids data gathering latency due to the low moving velocity of the mobile collector in the network. The observed information by performing proper local aggregation is then uploaded to the mobile collector through the nearest sensor nodes in the field. Before moving to the next site, a mobile sink stays at a site long enough so that entire data can be transferred from the sensors cache in the network.

In the proposed scheme, a mobile sink only needs to broadcast data collection message ($data\_msg$) in its vicinity once to inform a subset of nodes each time when it arrives at a new site for successful data gathering in the smart grid. The broadcast mechanism of a mobile sink to its neighboring nodes is shown in Fig. 3 (a). The data collection message contains the information about the moving velocity and location of the mobile sink. This method clearly minimizes energy consumption by avoiding network-wide broadcasting, especially in large-scale WSNs-based SG applications. Herein, the entire movement pattern of a mobile sink to collect data from the sensor nodes in a subnetwork has been divided into two main cycles. In first cycle a mobile sink moves with constant speed to predefined locations based on predictable mobility for data collection from the sensors in a subnetwork. Later in the second cycle a mobile sink gives priority and moves periodically to those sensors locations where there is a higher probability of events occurrence in a subnetwork. It could be obtained based on the prior movement history stored in the routing table of each mobile sink in the network. This mechanism helps to avoid nodes buffer overflow and latency of the events in the network. After completion of every cycle, each time the visiting decision is updated leading to precise sink movement for QoS-aware event data collection in the network. This phenomenon extremely reduces latency for various SG applications.

Consequently, as soon as the broadcasting process finishes, a mobile sink enters the valid dissemination range of some sensor nodes to collect data via short-range communications. Each sensor node intercepts the data collection message attempts to acquire the medium using CSMA mechanism and transmits the cached data directly to the mobile sink if it has not already sent its data to another associated mobile sink. The entire sensor node's cache data that are a single hop away can be transmitted directly nodes to the associated mobile sink based on FCFS policy.

The sensor nodes away from the mobile sink forward their observed information to the next hop node which is closer to the mobile sink based on its routing table in a greedy manner. On receiving the data message from the neighboring nodes, a relay node aggregates the data and forwards again to the next hop node further closer to the mobile sink. Finally, the received data by performing proper some local aggregation is then directly uploaded to the nearest mobile collector by a relay node through short distance communication in the network. Note that, herein, a next hop relay node is selected based on its higher energy and short distance information in the network. Herein, during data forwarding process the corresponding hop entry reduces by 1 in the routing table of each forwarding sensor node. This multi-hop data transmission using relay nodes significantly saves energy of the sensor nodes in the network. Moreover, it avoids data gathering latency due to the low moving velocity of the mobiles collector in the network. Consequently, a mobile sink waits for a specific time interval to receive the entire data from the sensor nodes in a sub-region. The transmitted data is then removed immediately from a sensor's memory to free cache for new event recordings in the smart grid. Finally, the collected data is forwarded to a BS by the mobile sinks directly or via multi-hop manner for user inspections as shown in Figs. 3(b) and (c), respectively. Note that, if a sensor node linked to two mobile sinks and already sent its data to one of the mobile sinks in the current cycle by following FCFS policy. Then, it simply ignores the advertisement message received from the mobile sink. Consequently, the regular sink movement nearer to the sensors helps to minimize the energy consumption due to the short distance data collection, thus increasing the network lifetime. Moreover, it solves the hotspot or energy hole problem in the network.

In addition, to distribute the energy consumption and data traffic load of the mobile sinks evenly among each other in the network. In designed scheme, a mobile sink away from the BS forwards its data through the nearby relay mobile sink only when two sinks move close enough in the network as shown in Fig. 3(c). During data forwarding process, a sink node broadcasts its current speed and location information to its neighboring mobile sinks in the network as shown in Fig. 3(d). After receiving message correctly each mobile sink replies to the sender mobile sink, including its location, speed, distance and residual energy information as shown in Figs. 3 (e) and (f), respectively. A next hop mobile sink with minimum distance and high energy residual energy above defined threshold value is selected as a relay mobile sink in the network. Then a sender mobile sink sends a ready data collection message ($ready\_msg$) to the selected next hop relay mobile sink. After receiving ready data collection message sender sends its data to the next hop relay node. The amount of data received from the neighboring mobile sinks to a sink nearer to the BS varies and depends on the number of sinks and their data gathering rates in the smart grid. Finally, the gathered data is forwarded over highly reliable links to a BS for user inspection in the smart grid.

(Figure 3)

4.2.3 Dead node detection and route recovery

In the proposed scheme, each mobile sink is equipped with the capability of finding a dead or inactive sensor and mobile sink in the network. To do so, each mobile sink periodically monitors its member sensor nodes by sending an alive message ($alive\_msg$) in the network. During monitoring cycles, if a sensor node does not reply to the sender sink in a predefined amount of time then it is assumed to be dead. To verify the dead node in a sub-region, a mobile sink limited broadcast a neighboring verify message (vfy_msg) once to its member sensor nodes based on their location information in the network. The sensor nodes which are able to decode the message accurately start communication by forwarding the verify message to the dead node based on its information stored in the routing table and wait for the reply in a predefined amount of time. Herein, it is important to that at least one sender sensor node must get a response from the assumed dead node in order to verify the node is alive otherwise is dead. After receiving verify message from the sensor nodes, a mobile sink informs to its member sensor nodes about the dead sensor node by sending a dead information message ($dinfo\_msg$) in the subnetwork. Later, the updated information about the dead node is forwarded to the users. The similar process is repeated for the mobile sinks in order to find a dead mobile sink in the network.

After the dead node announcement by a mobile sink, a new route formation starts again in a sub-region only if the dead node served as a relay node for its neighboring nodes in the network. Otherwise, a mobile sink does not announce route recovery message ($rrec\_msg$) to its member nodes in a sub-network. Consequently, a mobile sink starts to broadcast route recovery message to its member sensor nodes based on their location information in a sub-region. On receiving the message, a node that can decode the route recovery message correctly forwards this message to discover its neighboring relay nodes in a subnetwork. This entire process continues until all sensor nodes in a certain region have received the message correctly about their neighboring sensor nodes. However, if a node receives the multiple identical messages from the same neighboring node, it simply ignores the message. Then, based on the received information stored in the routing table of each node, a sensor node sends relay request message ($relay\_msg$) to the node which has the smallest distance towards the mobile sink in a sub region. After receiving a relay request message, the relay node sends an acknowledgement message to the sender node to ensure that the message has been received successfully. The main fields of the reply message are: selected relay node identity, residual energy, hops count and location information to the associated node. Herein, the value of hop distance for the nodes that are a single hop far from the sink is 0, however, increases iteratively in each sensor routing table by 1 as the number of hops increases to the corresponding intermediate node in the network. The update information of the relay node is the then forwarded to the associate mobile sink which marks its current location, residual energy and hops count in its routing table to facilitate the data collection at intermediate nodes in the network.

4.2.4 Mathematical Modeling

In designed scheme, we use mixed integer linear programming to model the network. Let the set of sensor nodes and mobiles sink are represented by $\mathcal{S}_i = \{\mathcal{S}_1 + \mathcal{S}_2 +, \dots, \mathcal{S}_n\}$ and $\mathbb{S}_k = \{\mathbb{S}_1 + \mathbb{S}_2 +, \dots, +\mathbb{S}_n\}$ deployed with their location information $\mathcal{L}_i = \{\mathcal{L}_1 + \mathcal{L}_2 +, \dots, +\mathcal{L}_n\}$ in sub-regions $\mathcal{R}_i = \{\mathcal{R}_1 + \mathcal{R}_2 +, \dots, +\mathcal{R}_n\}$ for monitoring events in smart grid. The set of links between each set of pair of sensor nodes in the network is shown by $\ell_i = \{\ell_{1(\mathcal{S}_1,\mathcal{S}_2)} + \ell_{2(\mathcal{S}_1,\mathcal{S}_3)} +, \dots, + \ell_{n(\mathcal{S}_n,\mathcal{S}_n)}\}$ while the set of stops of mobile sinks in different sub-regions over predefined paths for efficient data collection from the sensor nodes is indicated by $\mathcal{S}_i = \{\mathcal{S}_1 + \mathcal{S}_2 +, \dots, + \mathcal{S}_n\}$ and $\mathcal{P}_i = \{\mathcal{P}_1 + \mathcal{P}_2 +, \dots, + \mathcal{P}_n\}$, respectively, in the network. The set of distance between each set of pair of sensor nodes, sensors to mobile sink, mobile sink to another mobile sink and mobile sinks to the base station are represented as $\mathcal{D}_{\mathcal{S}_i}^{\mathcal{S}_j} = \{\mathcal{D}_{\mathcal{S}_1(\mathcal{S}_2)} + \mathcal{D}_{\mathcal{S}_1(\mathcal{S}_3)} +, \dots, + \mathcal{D}_{\mathcal{S}_n(\mathcal{S}_n)}\}$, $\mathcal{D}_{\mathbb{S}_k}^{\mathcal{S}_j} = \{\mathcal{D}_{\mathbb{S}_1(\mathcal{S}_1)} + \mathcal{D}_{\mathbb{S}_1(\mathcal{S}_2)} +, \dots, + \mathcal{D}_{\mathbb{S}_n(\mathcal{S}_n)}\}$, $\mathcal{D}_{\mathbb{S}_i}^{\mathbb{S}_k} = \{\mathcal{D}_{\mathbb{S}_1(\mathbb{S}_2)} + \mathcal{D}_{\mathbb{S}_1(\mathbb{S}_3)} +, \dots, + \mathcal{D}_{\mathbb{S}_n(\mathbb{S}_n)}\}$ and $\mathcal{D}_{\mathbb{B}_\mathbb{s}}^{\mathbb{S}_k} = \{\mathcal{D}_{\mathbb{S}_1(\mathbb{B}_\mathbb{s})} + \mathcal{D}_{\mathbb{S}_2(\mathbb{B}_\mathbb{s})} +, \dots, + \mathcal{D}_{\mathbb{S}_n(\mathbb{B}_\mathbb{s})}\}$ for $\forall i = 1,2, \dots, n$, $\forall i = 1,2, \dots, n$, $\forall k = 1,2, \dots, n$ and $\mathbb{B}_\mathbb{s} = 1$ in the network, respectively.

Consequently, the main purpose of the objective function (ϕ) in designed scheme is to maximize benefits by minimizing the total cost of the network.

$$\phi = \text{Max} \sum_{\mathcal{S}_i}^{\mathcal{S}_j} \sum_{\mathcal{S}_i}^{\mathbb{S}_k} \sum_{\mathbb{S}_k}^{\mathbb{B}_\mathbb{s}} \max\left(\mathbb{P}_{dr} + \mathbb{T}_p + \mathbb{N}_{lt}\right)^{ij,k\mathbb{B}_\mathbb{s}} + \text{Max} \sum_{\mathcal{S}_i}^{\mathcal{S}_j} \sum_{\mathcal{S}_i}^{\mathbb{S}_k} \min\left(\mathbb{D}_e + \mathbb{E}_c + \mathbb{M}_o + \mathbb{P}_{er}\right)^{ij,ik} \quad \forall i,j,k = 1,..,n \quad \mathbb{B}_\mathbb{s} = 1 \quad (1)$$

In Eq.1, $\mathbb{P}_{dr}$, $\mathbb{T}_p$, $\mathbb{N}_{lt}$, $\mathbb{D}_e$, $\mathbb{E}_c$, $\mathbb{M}_o$ and $\mathbb{P}_{er}$ are: the packet delivery ration, the network throughput, the network lifetime, the delay, the energy consumption, the memory/buffer overflow and the packet error rate in the network, respectively.

subject to:

$$\sum_{k=1}^{n} q_0(\mathbb{S}_k) \le \mathbb{S}_n, \quad \forall k = 1, \dots, m \quad (2)$$

$$\sum_{k=1}^{n} g_{1\mathbb{S}_k} = \sum_{k=2}^{n} g_{\mathbb{S}_k 1} = m \quad \forall k = 1, \dots, m \quad (3)$$

$$\min \sum_{\mathcal{S}_i \in \mathcal{S}_n} \sum_{\mathcal{S}_j \in \mathcal{S}_n} \mathcal{C}_{(\mathcal{S}_i,\mathcal{S}_j)} \sum_{k=1}^{n} \mathcal{N}_{(\mathcal{S}_i,\mathcal{S}_j)}^{\mathbb{S}_k} \quad \forall\, i,j, = 1, \dots, n \quad \forall k = 1, \dots, m \quad (4)$$

$$\sum_{\mathcal{S}_i \in \mathcal{S}_n} \mathcal{X}_{\mathcal{S}_i(\mathcal{L}_j)}(\mathbb{S}_k) \ge 1 \quad \forall i,j \in 1, \dots, n \quad \forall k = 1, \dots, m \quad (5)$$

$$\mathcal{X}_{\mathcal{S}_i(\mathcal{L}_j)} \le \mathcal{Y}_{\mathcal{S}_i(\mathcal{L}_j)}(\mathbb{S}_k) \quad \forall i,j \in 1, \dots, n \quad \forall k = 1, \dots, m \quad (6)$$

$$z_{\mathcal{S}_i} \le \sum_{\mathcal{S}_i \in (\mathcal{L}_j)} \mathcal{X}_{\mathcal{S}_i(\mathcal{L}_j)}(\mathcal{S}_i), \quad z_{\mathcal{S}_i} \le \mathcal{Y}_{\mathcal{S}_i(\mathcal{L}_j)} \times \mathcal{C}_{max}(\mathcal{S}_i), \quad \mathcal{C}_{max}(\mathcal{S}_i) < \mathcal{S}_n \quad \forall i,j \in 1, \dots, k \quad (7)$$

$$\sum_{\mathcal{S}_i \in (\mathcal{L}_j)} \mathcal{Y}_{\mathcal{S}_i(\mathcal{L}_j)}(\mathcal{E}\mathcal{S}_i) \le \mathcal{S}_{max}(\mathbb{S}_k) \quad \forall i,j \in 1, \dots, n \quad \forall k = 1, \dots, m \quad (8)$$

$$\sum_{\mathcal{S}_i \in (\mathcal{L}_j)} \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)} \mathcal{P}_{i\,\mathbb{S}_k}^{\mathcal{S}_i} \ge 1 \quad \forall i,j \in 1, \dots, n \quad \forall k = 1, \dots, m \quad (9)$$

$$\rho_r(\mathbb{S}_k) = 1 - \prod_{i=1}^{n}\left(1 - \rho_r \delta_i(\mathcal{S}_i)\right) \quad \forall i \in 1,\dots,n \;\; \forall k = 1,\dots,m, \mathbb{S}_k = 1,\dots,m, \delta_i = 1,\dots,n, \quad (10)$$

$$\sum_{j=1}^{n} \mathcal{H}_{(\delta_j)\mathcal{T}_i} + \hbar_{(\delta_i)\mathcal{T}_i} = 1, \quad \forall i,j \in 1,\dots,n \qquad (11)$$

$$\sum_{\mathcal{S}_i,\mathcal{S}_j \in (\mathcal{L}_k)} \mathcal{F}\ell_{1(\mathcal{S}_i,\mathcal{S}_j)} = \sum_{\mathcal{S}_j,\mathcal{S}_i \in (\mathcal{L}_k)} \mathcal{F}\ell_{1(\mathcal{S}_j,\mathcal{S}_i)} \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (12)$$

$$\sum_{\mathcal{S}_i,\mathcal{S}_j \in (\mathcal{L}_k)} \mathcal{F}\ell_{1(\mathcal{S}_i,\mathcal{S}_j)} + \mathcal{F}\ell_{1(\mathcal{S}_j,\mathcal{S}_i)} \le 1 \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (13)$$

$$\sum_{\mathcal{S}_j \in (\mathcal{L}_i)} \mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)} (\mathcal{DP})_j > \sum_{\mathcal{S}_i \in (\mathcal{L}_i)} \mathcal{S}_i(\mathcal{L}_k) \cdot (\mathcal{DP})_i \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (14)$$

$$\sum_{\mathcal{S}_i \in \mathcal{S}_n} \mathbb{E}_{\mathcal{S}_i}^{\mathcal{S}_j}(\delta_k) \le \mathbb{E}_0 \quad \forall i = 1,\dots,n \quad \forall \mathrm{k} = 1,\dots,\mathrm{m} \; (15)$$

$$\mathcal{T}_{\delta_k} \ge 0, \quad \forall \mathrm{k} = 1,\dots,\mathrm{m} \quad (16)$$

$$\mathcal{W}_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)}} = \sum_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)} \in \mathcal{S}_n} \mathcal{A}_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)}} \times \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)} \le 1 \quad \forall i,j \in 1,\dots,n \quad (17)$$

$$\sum_{\mathcal{S}_j \in (\mathcal{L}_i)} \mathcal{B}_{\mathcal{S}_j(\mathcal{L}_i)} \mathcal{P}_{i_{\mathbb{S}_k}}^{\delta_i} = \sum_{\mathcal{S}_j \in (\mathcal{L}_i)} \mathcal{B}_{\mathcal{S}_j(\mathcal{L}_i)} \mathcal{P}_{i_{\mathbb{S}_k}}^{\delta_i} \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (18)$$

$$\sum_{\mathcal{S}_j:(\delta_j,\mathcal{S}_j)} \mathcal{F}_{\delta_j,\mathcal{S}_j}^{\mathbb{S}_k} = \sum_{\mathcal{S}_j:(\mathcal{S}_i,\delta_i) \in A^k} \mathcal{F}_{\mathcal{S}_i,\delta_i}^{\mathbb{S}_k} = 1 \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (19)$$

$$\sum_{\mathcal{S}_i:\mathcal{S}_i,\mathcal{S}_j \in \mathbb{S}_k} \mathcal{F}_{\ell_1(\mathcal{S}_i,\mathcal{S}_j)}^{\mathbb{S}_k} - \sum_{\mathcal{S}_j:\mathcal{S}_j,\mathcal{S}_i \in \mathbb{S}_k} \mathcal{F}_{\ell_1(\mathcal{S}_j,\mathcal{S}_i)}^{\mathbb{S}_k} = 0 \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (20)$$

$$\sum_{\mathcal{S}_i \in (\mathcal{L}_j)} \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)} \mathcal{U}_{\mathbb{S}_k}^{\delta_i}, \quad \delta_i \le 1 \quad \forall i,j \in 1,\dots,n \;\; \forall k = 1,\dots,m \quad (21)$$

$$\sum\nolimits_{\delta_j \in \delta_n} \mathcal{X}_{1(\delta_i\delta_j)}^{\mathbb{S}_k} - \sum\nolimits_{\delta_j \in \delta_n} \mathcal{X}_{1(\delta_j,\delta_n+\delta_i)}^{\mathbb{S}_k}, \quad \forall i,j \in 1,\dots,l \;\; \forall k = 1,\dots,m \qquad (22)$$

$$\mathcal{T}_{\delta_i} + S_{\delta_i} + t_{\delta_i,\delta_n+\delta_i} \le T_{\delta_n+\delta_i}, \quad \forall i,j \, \{1,\dots,l\} \quad (23)$$

$$\delta_i + (\delta_k - 2)\mathscr{b}_{1\delta_i} - \mathscr{b}_{\delta_i 1} \le \delta_k - 1, \quad i = 2,..,n, \quad k = 1,\dots,k \quad (24)$$

$$\delta_i + \mathscr{b}_{1\delta_i} + \left(2 - \delta_j\right)\mathscr{b}_{\delta_i 1} \ge 2, \quad i = 2,..,n, \quad j = 1,\dots,m \quad (25)$$

$$\delta_i + \mathscr{b}_{1\delta_i} \le 1, \quad i = 2,\dots,n, \quad (26)$$

$$\sum_{\mathcal{S}_j\in(\mathcal{L}_i)} \mathcal{Z}_{\mathcal{S}_j(\mathcal{L}_i)}\,(\mathcal{DP})_i = \sum_{\mathbb{S}_k\in\mathbb{S}_n} \mathcal{Z}_{\mathcal{P}_{i_{\mathbb{S}_k}}^{\delta_i}} \left(\mathcal{S}_j(\mathcal{L}_i)\right)^{(\mathcal{T}_{\mathcal{DP}})_i} = \sum_{\mathbb{B}_{\mathbb{s}}=1} \mathbb{Bs}\,(\mathcal{T}_{\mathcal{DP}})_i \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (27)$$

$$\omega_{\delta_i(\mathbb{S}_{\mathcal{T}_i}^k)} = \sum_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)},\mathcal{S}_i(\mathcal{L}_j)\in\mathcal{S}_n} \left(\mathcal{A}_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)}} \times \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)}\right)^{\mathcal{T}_i} \le \omega_{max} \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (28)$$

$$\delta_i(\mathbb{S}_{\mathcal{T}_i}^k) = \sum_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)},\mathcal{S}_i(\mathcal{L}_j)\in\mathcal{S}_n} \left(\mathcal{A}_{\mathcal{R}e_{\mathcal{S}_j(\mathcal{L}_i)}} \times \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)}\right)^{\mathcal{T}_i} \mathcal{P}_{i_{\mathbb{S}_k}}^{\delta_i} \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (29)$$

$$\mathbb{Bs}(\mathcal{T}_j) - \delta_i(\mathbb{S}_{\mathcal{T}_i}^k) \le \mathcal{T}_{max} \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (30)$$

$$\mathcal{D}_{\mathbb{S}_k}^{\mathcal{S}_j} = \min \frac{2}{\mathfrak{R}^2} \int_0^{\mathfrak{R}} \mathbb{E}_1(\mathrm{r})\hbar(\varkappa,\mathrm{r})\varkappa \mathrm{d}\varkappa \quad (31)$$

$$\mathcal{U}_{\mathbb{S}_k(\delta_i,\delta_j)} \ge \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)} \cdot \mathcal{P}_i(\delta_i,\delta_j) \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (32)$$

$$\sum_{\mathcal{S}_i\in(\mathcal{L}_j)} \mathcal{B}_{\mathcal{S}_i(\mathcal{L}_j)}\,\mathcal{P}_{i_{\mathbb{S}_k}}^{\delta_i},\ \ (\mathcal{P}_i)^{\delta_i} \ne (\mathcal{P}_j)^{\delta_j} \quad \forall i,j \in 1,\dots,n\ \forall k=1,\dots,m \quad (33)$$

$$\sum_{i=1}^{r_n} \mathcal{U}_{\mathbb{S}_k}^{\mathcal{P}_j}\ \mathbb{S}_k(\mathcal{R}_{\mathscr{b}}) \ge 1, \quad \mathbb{S}_k \in \mathbb{B}_{\mathbb{s}} \quad \forall j \in 1,\dots,n\ \forall k=1,\dots,m \quad (34)$$

$$\sum_{k=1}^{n} \mathbb{S}_k(\mathcal{R}_{\mathscr{b}}) = 0, \quad \mathbb{S}_k \in \mathbb{B}_{\mathbb{s}} \quad (35)$$

Constraints (2) ensure that all mobile sink starts from the base station. Constraints (3) ensure that exactly m mobile sinks depart from and return back the base station. The objective function of the Eq.4 is to minimize the total travelled distance by all mobile sinks in the network. Constraints (5) ensure that each sensor node is associated to at least one mobile sink in the network. Constraints (6) guarantee that a sensor node could only be assigned to at least one mobile sink stop that exists. Constraints (7) computes the used capacity of each created mobile sink stop (δ_i) and ensures that the mobile sink stop capacity is not exceeded. Constraints (8) ensure that the total number of mobile sink stops generated is not greater than the maximum number of stops established ($\mathcal{E}\delta_i$). Constraints (9) ensure that each mobile sink stop over a defined route is at least visited once time by a mobile sink in the network. Eq.10 shows the probability of a mobile sink covering the number of sensor nodes at stop δ_i in the network. It also ensures that once a mobile sink visits a stop must also depart from the same stop in the network. Constraints (11) ensure that the mobile sink is either at a stop, or it is moving. Constraints (12) ensure the continuity of data flow in the intermediate sensor nodes in the entire network. Constraints (13) avoid the formation of path loops among the intermediate sensor nodes in the network. Constraints (14) ensure that all relay sensor nodes carry more data traffic than the sensor nodes that does not relay the data packets to the associate mobile sink in the network. Constraints (15) assure that the energy consumed at each sensor node $\mathcal{S}_i$ must not exceed the initial energy of that sensor node in the network. Constraint (16) simply states the non-negativity of stop time $\mathcal{T}_{\delta_k}$ in the network. Constraints (17) ensure that the total number of data packets received of a node by the neighboring sensor nodes must not exceed its maximum limit to avoid buffer overflow during data forwarding process in the network. Constraints (18) ensure the continuity of data flow from the sensor nodes to the mobile sink stops in the network. Constraints (19) and (20) are network constraints, and ensure that one unit of data must be sent from the source sensor node to the mobile sink in each subnetwork. Constraints (21) guarantee that each mobile sink does not leave the same $stop$ more than once over a defined path in the network. Constraints (22) ensure that the same mobile sink $\mathbb{S}_k$ visits both stops δ_i and $\delta_n + \delta_i$. Constraints (23) are precedence constraints which forces a mobile sink that a stop δ_i to be visited before $\delta_n + \delta_i$. In Eq. 25 and 26, δ_i is the number of stops visited by a mobile sink on a defined path from the source up to end δ_n. δ_k is the maximum number of sensor nodes a mobile sink may visit, i.e., $1 \le \delta_i \le \delta_k$ for all $i \ge 2$. Moreover, let δ_j be the minimum number of stops a mobile sink must visit such that if $\mathscr{b}_{i1} = 1$, otherwise 0, then condition $\delta_j \leq \delta_i \leq \delta_k$ must be satisfied in the network. Constraints (24) and (25) are bounding constraints and the inequalities presented in both serve as upper and lower bound constraints on the number of stops visited by each mobile sink. It initializes the value of δ_i to 1 if and only if i is the first stop on the tour for a mobile sink in the network. In constraints (26), the inequality forbids a mobile sink from visiting only a single stop in the network. Constraints (27) ensure that total numbers of packets sent by the sensor nodes to their associated mobile sinks are equal to the total number of data packets received by a base station in the network. In Eq. 29, 30 and 31, $\mathcal{T}_i$ is the data collection time of a mobile sink along a defined path at distinct stop in a sub-area of the network. Constraints (28), (29) and (30) are the time constraints. Constraints (28) ensure that the waiting time of a mobile sink to collect data from the sensor nodes at a distinct stop in a sub-area does not exceed the maximum waiting time. Constraints (29) and (30) ensure that the maximum data collection time between the sensor nodes and mobile sink at a distinct stop in a sub-region reaches to the base station must not exceed the defined maximum time. Eq. 31 is averaging of all possible minimum distances from the sensor node of interest to the mobile sink. Constraints (32) ensure that there are only paths between stop δ_i and δ_j for the mobile sink $\mathbb{S}_k$, if the mobile sink is active. Constraints (33) guarantee that each mobile sink only visits it own stops over a defined route and does not enter the stops of another mobile sink in the network. Constraints (34) ensure that all the used mobile sinks after finishing the round numbers have a stop at least once in the base station in order to recharge/replace their batteries $\mathcal{R}_{\mathscr{b}}$. Finally, the constraints (35) ensure that no direct path between the base station and the mobile sinks from the sensor nodes located in a sub-region is created for any mobile sink in order to recharge/replace their batteries.

(Table.2)

5. Path Loss and Simulation Models

In the current study, log-normal shadowing path-loss model presented in [23] is used, due to its providing more accurate channel estimation results compared to the Rayleigh and Nakagami models in a smart grid environment, can be formally indicated as:

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta log_{10} \frac{d}{d_0} - X_\sigma - P_\eta$$

in which $\gamma(d)$, P_t, $PL(d_0)$, η, X_σ, and P_η are: the signal to noise ratio (SNR), the transmit power in dBm, the path loss at reference a distance d_o, the path-loss exponent, the zero mean Gaussian random variable with standard deviation and the noise power measured in dBm. In smart grid environments, the values of noise floor, shadowing deviation (σ) and path loss exponent (n) for both line of sigh (LOS) and non-line of sight (NLOS) are given in Table. 3.

Moreover, the performance of MQRP was evaluated extensively using a network simulation tool called EstiNet9.0. Due to lack of an appropriate mobility–based data gathering protocol in the literature, the obtained experimental facts were analyzed and compared against the well-known recent published routing protocol called SinkTrail [42] in the smart grid environments. In addition, ninety-five percent (95%) confidence intervals are also shown for each data point using batch mean method [43] in order to provide the consistent results. The parameters used in this simulation are given in the following Table.3.

(Table.3)

6. Performance Evaluations

In this section, the performance of MQRP against the SinkTrail for the smart grid emergency response applications has been realized using several widely used metrics that depict the behavior of the schemes are defined as below: (1) packet delivery ratio (2) data loss rate (3) throughput (4) delay (5) memory utilization (6) minimum required speed (7) control message overhead and (8) residual energy. The packet delivery ratio is defined as the ratio of packets successfully received at the BS to the total number of packets sent by a sensor node in the network. We define data loss rate as the ratio of the data lost due to node buffer overflow to the total amount of data generated in the network. Throughput is the rate at which a number of packets received at the base station at a given time (bits/seconds) in the network. Delay is the time taken by a data packet sent along the shortest path from the source and received successfully at the BS. Memory utilization is the efficient memory utilization of a sensor node to avoid information loss during receiving and sending information in the network. Minimum speed required is the minimum speed of the mobile sink to prevent any node buffer overflow in the network. Control message overhead is the number of destination location update search messages received rather than the number of control messages transmitted by the sensor nodes in the network. Finally, residual energy is the amount of remaining energy after energy consumed to route one bit of information from the source to the destination in the network. Where the energy consumption is the sum of idle energy consumption, data aggregation, transmission and reception of control packets, and energy consumption of actual data transmission and reception in the network.

Fig.4 (a) shows the packet delivery ratio of both MQRP and SinkTrail data collection schemes for emergency response applications in the smart grid. It clearly shows that the packet delivery ratio of MQRP is higher than the SinkTrail scheme in the smart grid. Fig.4 (b) shows the mobile sink varying speeds from 0 m/s to 2 m/s, in the smart grid. It clearly shows that the data loss rate for emergency response applications decreases with the decrease in speed of the mobile sink from 100 to 0, which correspond to the complete loss cases and no loss, respectively, in the smart grid. Herein, it should be noted that the data loss rate also increases with the increase in speed of the mobile sink if it is higher than a certain threshold value for emergency response applications in the smart grid. Our findings indicate that compared to SinkTrail, the data loss rate of MQRP data collection scheme drops rapidly at a higher rate with the increase in the mobile sink for emergency response applications in the smart grid. For speed close to 1.8m/s, it achieves a success rate close to 95%, with minimum latency and full sub-network coverage ranging from 95% to 97% in the smart grid. When the speed of the mobile sink is close to 2m/s, its success rate is observed close to 100%, extremely minimum latency and full sub-network coverage ranging from 99% to 100%, with the minimum expense of increasing energy utilization in the smart grid. On the other hand, SinkTrail for the speed close to 1.8m/s and 2m/s, it achieves a success rate close to 89% and 91%, higher delay and full coverage of the sub-region 85% and 90%, respectively, at the expense of high energy consumption in the smart grid. Thus, the coverage set about 90%, meaning that an average of 10% sensor nodes remains unvisited by the mobile sink in the sub-regions in the smart grid. This provides an evidence that the SinkTrail needs a lot of time to cover the entire sub-networks area. Thus, to increase its lower success rate, it needs to improve the mobile sink moving speed for collecting all of the sensor nodes data in the smart grid.

In more details, we also observe that the minimum required speed of the mobile sinks in the entire sub-regions increases with the increasing node density to avoid buffer overflow in the smart grid. This leads to increase the path length, which results in higher mobile sink speed to avoid buffer overflow in the network. In most cases, compared to SinkTrail, the minimum required speed of the mobile sink in MQRP is lower for efficient data collection from the sensor nodes on the same topology. However, it is above the minimum required speed so that each sensor limited memory did not be overflowing at the time when a mobile sink visits them in a particular sub-region in the smart grid. Hence, the data loss rate is very small due to visiting several sensor nodes in a certain time span in the network. In MQRP compared to SinkTrail, sensor nodes with respect their overflow times are better distinguished by the mobile sink in each sub-region in the smart grid. Therefore, the data loss rate is decreased by frequently visiting a set of sensors having high overflow times compared to those with low overflow times in the smart grid. This effectively increases the packet delivery ratio of MQRP for emergency response applications in the smart grid. In SinkTrail, the lower speed of the mobile sink than the minimum required speed sacrifices the low overflow times the sensor nodes performance in each sub-area in the network. Thus, its advantage of smaller data loss and delay disappear for moderate and high speeds when a mobile element moves at lower speeds for smart grid emergency response applications in deterministic topology settings.

Fig. 4 (c) shows the impact of buffer size ranging from 1 MB to 5 MB on data loss rate from 100 to 0 when the mobile sink is running at the speed from 0 m/s to 2 m/s for both MQRP and SinkTrail schemes in the smart grid. The data loss rate of MQRP drops to 0 when the memory size is about 4.3 MB and the mobile sink moves at a speed of 2 m/s. On the other hand, in SinkTrail still, above 10% of the information is lost even when the memory size is 5 Mb at the same running speed of the mobile sink. Herein, it is also observed that the data loss rates decrease as buffer size increases for both MQRP and SinkTrail schemes in the smart grid. However, the decrease in data loss rates in MQRP is observed higher compared to SinkTrail scheme in the smart grid. Generally, in MQRP all sensor nodes due to their efficient memory management have large overflow time, which results in more capacity to carry information even when the event occurrence rates are high in different sub-regions in the network. Consequently, with increasing memory size the data loss rate rapidly decreases, and helps the mobile sink running at the dynamic speed to collect more data in the smart grid. Moreover, the designed scheme provides periodic scheduling based on event occurrence rates to observe the predictability of sensor nodes by visiting multiple times in each sub-area in the smart grid. Therefore, the designed scheme favors each mobile sink to visit frequently and more periodically the sensors regions have smaller overflow times compared to high overflow times in the network. However, the inter-visit times of a set of mobile sinks for the given sensors in a cycle are not necessarily equally spaced due to the higher periodicity of visiting the sensors in a sub-area in the smart grid. Therefore, the sensor nodes transmission times positioned in different sub-regions are not always the same with some small variations due to the different length of cycles.

In Fig 4 (d), we examine the performance of MQRP and SinkTrail in term of efficient memory utilization of the sensor nodes for emergency response applications in the smart grid. We first notice that the designed scheme performs very well when the frequency of a mobile sink visits a set of sensors increases in the smart grid. In MQRP, the memory efficiency rate reaches to 98%, at low energy consumption and delay for emergency response applications in the smart grid. The SinkTrail also achieves a success rate ranging from 90% to 93%, but with higher delay, energy consumption and lower coverage compared to MQRP. So far based on our findings, the mobile sink in MQRP visits the whole sub-networks area faster than average low speed. Therefore, it equalizes the visits in each area due to its learning ability based on its previous iterations stored in the routing table. Consequently, all the available data is collected from the node's memory in a timely manner by visiting multiple times each sub-region in the smart grid. On the other hand, in SinkTrail a mobile sink most of the times remain around relatively deep areas and it requires a significant amount of time for visiting new sub-regions, hence a mobile sink certainly not visits all sub-regions in the smart grid. This, in fact, leads to nodes buffer overflow due to high visiting latency and poor memory management efficiency ranging 7% to 8% in the network, which reduces the packet delivery ratio of SinkTrail in the smart grid.

Fig.4 (f) shows the throughput performance by varying the number of sensors from 1 to 300 for both MQRP and SinkTrail data gathering schemes. In the simulation results, it can be clearly seen that the proposed scheme outperforms the SinkTrail approach, in term of high throughput. This is because of the reason that, in SinkTrail approach, sensor nodes close the mobile sink vulnerable to energy hole and hotspot problem due to inappropriate handling the heavy data traffic coming from the neighboring sensors in the smart grid. In some cases, received information cannot be forwarded to the mobile sink due to the energy hole in the deployed smart grid network. This problem got worse if all the sensor nodes information is being forwarded to the same relay node nearer to the mobile sink, which results in lower throughput across that sub-region in the smart grid. On the contrary, in MQRP due to steady mobile sink movement the relay node and immediate neighboring sensors of the relay changes. Consequently, the hotspot problem is reduced and more packets can be forwarded to the mobile sinks from the entire sub-regions in the smart grid. That is why MQRP has better throughput than SinkTrail for emergency response applications in the smart grid.

Fig.4 (g) shows that the designed scheme significantly improves the data delivery delay in general. On the contrary, we experience longer delays in SinkTrail compared to MQRP for emergency response applications in the smart grid. This is because of the mobile sink, which avoids areas having a number of nodes outside their area of service caused by partial network coverage, is not frequently visited by any mobile sink. In the beginning, the delay in MQRP is observed high due to its deterministic sinks movement for data collection in the sub-regions. However, with the passage of times, the level of delay rapidly decreases when the mobile sink switches to its dynamic movement pattern based on its learning ability in each sub-region. Moreover, in MQRP, most sensor nodes one hop away from the mobile sink always directly upload their buffered data when it passes multiple times close enough to the nodes in the smart grid. For the sensor nodes, two hops or three hops away from the sink most of the times results in a small relay hops for local data aggregation that reduces the possible tour length in MQRP compared to SinkTrail in the smart grid. In MQRP scheme, the average number of relays evidently decreasing because of the considering transmission range of sensors, which offers an opportunity to shorten the moving tour length of the mobile sink by selecting a fewer number of stops. This provides sensor nodes much opportunity to be linked with the node nearer the mobile sink stops by following the bounded relay hops constraint in the network. Thus, it becomes easier for the sensor nodes to communicate with each other as well as to the mobile sink with a small number of relay hops in the network. On the contrary, the average delay in SinkTrail is higher due to its deterministic sinks movement for data collection in the sub-regions. In addition, extremely high and low speeds of the mobile sinks are the other main issues leading to excessive delay in the network.

In addition to success rate, during multi-hop data forwarding process in SinkTrail, the performance drops significantly and energy consumption increases with the increase in hops count in the smart grid as shown in Fig. 4 (i). For three numbers of hops, it attains utmost success rate of 92%, compared to 70−83% for six numbers of hops in the smart grid. The energy consumption and delay for 5 hops are higher compared to 2 hops due to the constructed deeper routing paths towards the mobile sink. We observe that for 6 hops, the success rate rapidly drops due to propagating messages over several hops with larger distance towards the mobile sink in SinkTrail. This increases the probability of corrupted data packets, invalid data packets due to path loops, excessive delay and unbalanced energy consumption in the network. Moreover, the data traffic burden of sensors that are a single hop away from the mobile sink stop also increases due to relaying a large number of messages from the rest of the sensors in the smart grid. This most of the times result in data packet loss due to node buffer overflow problems in SinkTrail. In addition, most of the times due to rapid sink movement, sensors away from the mobile sink do not have enough time to convey all messages to the sink. This leads to excessive message re-transmissions and loss of a certain amount of data packets in harsh nature smart grid environments. Furthermore, in SinkTrail more than 95% sensor nodes got an opportunity to communicate with the sink, however, due to the lack of taking into account the harsh nature smart grid environments during multi-hop propagation several messages were not delivered to the mobile sink. In addition, the updating propagation route on time is very challenging for the mobile sinks in SinkTrail, thus messages follow outdated paths until a new route is established results in dropping data success rate in the smart grid. Furthermore, at each hop poor and unstable link quality between sensor nodes due to the harsh nature of the smart grid environments also generates a significant amount of corrupted data packets in the smart grid as shown in Fig.4 (e).

On the other hand, we observe that the performance significantly increases in terms of success rate with equally distributed low energy consumption in the smart grid. In the designed scheme, deeper constructed routing paths are avoided by setting a maximum number of 3 hops towards the mobile sink. Therefore, it achieves high success rates 99% and 96% for 2 hops and

3 hops with low energy consumption, respectively. The delay in both cases is observed very low compared to the SinkTrail data collection scheme, which fully satisfy the smart grid emergency response application requirements in the smart grid. In MQRP, a mobile sink achieves full coverage of the sensors in shorter time located in a larger sub-region and collects at least one packet from almost all sensor nodes in the smart grid. In addition, in term of a route failure the nodes in SinkTrail, most of the times fail to find alternative routes opportunistically towards the mobile sink stop or other certain sensors might be disconnected in the network. This most of the time results in bottlenecks, which slightly drops the packet delivery ratio in the smart grid. We also notice that due to frequent location updating and caused by frequent node failure the overhead in propagation route creation and reconfiguration leads to excessive nodes energy consumption leads to lower network residual energy as shown in Fig.4 (h) and Fig.4 (i), respectively. Thus, the network lifetime decreases rapidly in SinkTrail compared to MQRP in the smart grid. On the contrary, the designed scheme quickly detects and reconfigures a broken link at low overhead, thus consumes less energy, which prolongs the network lifetime for emergency response applications in the smart grid.

In the end, our findings based on performed simulation studies also indicate that the zone partitioning has a great impact on the energy consumption and energy utilization efficiency in both MQRP and SinkTrail data collection schemes. As expected, the energy utilization efficiency of the sensor nodes increases as the number of zone increases in the smart grid. In addition, the trajectory length also significantly affects the performance of deterministic mobility over a defined route in the sub-zones. The energy dissipation increases and data success rate rapidly drop with the increase in the length of the trajectory in the network. In MQRP, the mobile sink attempts to reduce the round trip time by minimizing the route length to visit the sensor nodes, which positively decrease the delay and energy consumption. Because of a better balance between data traffic and energy dissipation, the network lifetime of MQRP is longer than SinkTrail in the smart grid. In sum, all the above-mentioned facts indicate that the proposed scheme is appropriate and extremely suitable for the diverse smart grid applications compared to SinkTrail.

(Figure.4)

7. Conclusions and Future Work

Recently, the proliferation of IoT and WSNs has emerged a paradigm that paves the way for the fourth stage of electricity industrialization, known as the smart grid industry (SGI) 4.0. The key aim of SGI 4.0, is to wirelessly connect and integrate existing power system components that are generally located in different remote places for more efficient, reliable, and intelligent operations to improve economic benefits. In this respect, WSNs play a key role in enabling the vision of SGI 4.0. However, unique smart grid environments pose great challenges to guarantee reliable communication for WSNs-based SG applications. This results in deteriorating the QoS requirements as well as the network lifetime of multi-hop communication-based WSNs for SG applications to empower SGI 4.0. Understanding the facts, in this paper we proposed a novel multi-mobile sinks-based QoS-aware data gathering protocol for WSNs-based SG applications. The proposed scheme significantly improves the QoS performance metrics for WSNs-based SG applications and is suitable for both sparse and large network deployment. We evaluated the proposed scheme by using a network simulation tool called EstiNet9.0. The extensive performance evaluations show that the protocol has successfully achieved its defined goals in terms of packet delivery ratio, packet error rate, end-to-end delay, throughput, memory utilization, control message overhead and energy efficiency compared to existing routing schemes. However, some applications, such as wide-area situational awareness, substation, and distribution automation are still challenging due to their unique latency requirements. As for future research directions, the appropriate number of mobile sinks and novel sink speed control mechanism could be a promising solution to reduce further communication latency for SG applications. Moreover, the designed scheme could be further explored and analyzed in random sensor nodes deployments with a single or multi-mobile sinks for various SG applications. In addition, designing a new cross-layer communication protocol equipped with parallel computation characteristics could also be promising to reduce further communication delay, and the development of such protocol is left as a future work.

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Conflicts of Interest
None

Table.1.QoS requirements of the smart grid applications [22, 33, 44]

Applications	Security	Bandwidth	Reliability	Latency
Home energy management (HEM)	High	9.6-56kbps	99.0-99.99%	300-2000ms
Advanced metering infrastructure (AMI)	High	10-100kbps per node, 500kbps for backhaul	99.0-99.99%	2000ms
Price signalling (PS)	High	9.6-56kbps	99.0%	2000ms
Automated feeder switching (AFW)	High	9.6-56kbps	99.0%	1000ms-2000ms
Demand response management (DRM)	High	14-100kbps per node	99.0%	500-ms - several minutes
Outage management (OM)	High	56kbps	99.0%	2000ms
Distribution management (DM)	High	9.6-100kbps	99.0-99.99%	100 ms-2 second
Outage management (OM)	High	56kbps	99.0%	2000 ms
Distribution generation (DG)	High	9.6-56kbps	99.0%	2000 ms
SCADA	High	56-100kbps	99.0%	2000-5000ms
Asset management (AM)	High	56kbps	99.0%	2000ms
Meter data management (MDM)	High	56kbps	99.0%	2000ms
Overhead transmission line monitoring	High	9.6-64kbps	90.0%	1000ms
Distributed energy resources and storage	High	9.6-56kbps	99.0-99.99%	300 ms-2 sec
Vehicle to grid (VG)	High	9.6-56kbps	99.0-99.99%	2sc-5 min
Electrical vehicles (EV)	High	9.6-56kbps	99.0-99.99%	2sc-5 min
Residential energy management (REM)	High	9.6-56kbps	90.0%	1000ms
Building automation (BA)	High	9.6-56kbps	90.0%	2000ms
Substation Automation (SA)	High	9.6-56kbps	99.0-99.99%	15-200ms
Distribution Automation (DA)	High	9.6-56kbps	99.0-99.99%	15-200ms
Wide-Area Situational Awareness (WSA)	High	9.6-56kbps	99.0-99.99%	15-200ms

Table.2 Notations used in MQRP

Notation	Description
$\mathcal{q}$	is a binary variable. The value of $\mathcal{q}$ is 1 if a mobile sink $\mathbb{S}_k$visits a stop δ_i, 0 otherwise
$\mathcal{g}$	is a binary variable. The value of $\mathcal{g}$ is 1 if a mobile sink uses a link on the tour, 0 otherwise
$\mathcal{C}$	is the traveling cost of a mobile sink between two stops δ_i and δ_j and $\mathcal{N}$ is the number of times a mobile sink $\mathbb{S}_k$ visits stops δ_i and δ_j in the network
$\mathcal{X}$	is a binary variable that sets the assignment of the sensor node $\mathcal{S}_i \in \mathcal{L}_j$ to the stop created in a mobile sink $\mathcal{S}_i \in \mathbb{S}_n$
$\mathcal{Y}$	is a binary variable for the existence of a stop in a mobile sink such that $\mathcal{S}_i \in \mathbb{S}_n$ in the network
$\mathcal{z}$	is an integer variable that represents the number of sensor nodes that are assigned to a mobile sink stop located in node $\mathcal{S}_i \in \mathbb{S}_n$
$\mathcal{C}_{max}(\mathcal{S}_i)$	is the maximum node of sensor nodes associated with a mobile sink in the network.
$\delta_{max}(\mathbb{S}_k)$	is the maximum stop locations of a mobile sink in the network
$\mathcal{B}$	is a binary variable that identifies if $\mathcal{S}_i \in \mathcal{L}_j$ in the route $\mathcal{P}_i$ of a mobile sink $\mathbb{S}_k \in \delta_i$ in the network
$\mathcal{F}$	is a b binary variable that identifies the data flow between the intermediate sensor nodes $\mathcal{S}_i$ and $\mathcal{S}_j$ over highly reliable links $\ell_i(\mathcal{S}_i, \mathcal{S}_j)$ or a mobile sink $\mathbb{S}_k$ uses link $\ell_i(\mathcal{S}_i, \mathcal{S}_j)$ in the network. It takes the value 1 if a link is active and 0 otherwise
$\mathcal{U}$	is a binary variable that identifies if a distinctive mobile sink $\mathbb{S}_k \in \mathbb{S}_n$ was used to transport the data from the sensor nodes over a define path $\mathcal{P}_i$ in the network
$\mathcal{Z}$	is a binary variable that represents the number of sensor nodes sent their data packets ($\mathcal{DP}$)and total number of received data packets ($\mathcal{T}_{\mathcal{DP}}$) by the associated mobile sinks and a base station in the network
ω	is an integer variable that represents the waiting time of a mobile sink for data collection from its member sensor nodes in a sub-region at a distinct stop δ_i
ρ_r	is the probability
$\mathbb{S}_{\mathcal{T}_i}^k$	is the data collection time ($\mathcal{T}_i$) of a mobile sink ($\mathbb{S}_k$)along a defined path at distinct stop in a sub-area of the network
r_n	is the total number of rounds in the network
$\mathcal{Re}$	indicates the relay node.
$\mathcal{W}$	denotes the integer variables that represents the number of sensor nodes data packets that are picked up/dropped off at a stop in a sub-region
$\mathcal{A}$	shows the array with the number of sensor nodes data packets that are picked up/dropped off at relay sensor node $\mathcal{S}_j$ at location $\mathcal{L}_i$ in the network
ω_{max}	represents the maximum defined waiting time
$\mathcal{T}_{max}$	is the maximum defined time
$\mathcal{H}_{(\delta_j)\mathcal{T}_i}$	is a binary variable that has the value 1 at the time $\mathcal{T}_i$ when mobile sink is at stop δ_j, 0 otherwise.
$\hbar_{(\delta_i)\mathcal{T}_i}$	is a binary variable that has the value 1 at the time $\mathcal{T}_i$ when mobile sink is moving, 0 otherwise.
$\mathbb{E}_{\mathcal{S}_i}^{\mathcal{S}_j}(\delta_k)$	is the energy consumed for receiving and transmitting data to the sensor node $\mathcal{S}_i$ during the time interval the mobile sink stops $\mathcal{S}_k$ at node in the network.
$\mathbb{E}_0$	is the initial energy of the sensor nodes in the network
$\mathbb{E}_1(\mathrm{r})$	is the anticipated amount of energy spent by the one-hop transmission of a sensor node at a distance $\varkappa$ away from the mobile sink in the network
$\hbar(\varkappa, \mathrm{r})$	is the anticipated number of hops that sensor's packet need to make to reach the mobile sink in the network
$\mathfrak{R}$	is the radius of a sensor node in the network

Table.3 Simulation and log-normal shadowing model parameter values

Simulation Model Parameters	Values
Deployment area (length × width)	1400 × 800 meters (m)
Grid Station (outdoor)	500kV
Total number of sensor nodes	300
Physical layer standard	IEEE802.11g
Initial sensor node energy	5 joules (J)
Initial energy of the mobile sink	10kJ
Sensor node maximum communication range	85 m
Sensor node maximum transmission power	0.93 watts (W)
Sensor nodes packet receiving power	0.035 W
Sensor nodes maximum data transmission rate	256 kbps
Sensor node buffer size	5 Megabit (Mb)
Ideal listening	0.013 W
Sleeping power	3×10^{-6} W
Data aggregation	0.013 W
Antenna Beamwidth for both sink and sensor (Omni-direction)	360^{o}
Packet length	53 bytes
Maximum velocity of the mobile sink	2 m/seconds
Number of mobile sinks	5
Number of zones	5
Topology	Deterministic
Number of simulations	59
Path loss exponent (n) for both LOS, NLOS	2.4
Noise floor for both LOS, NLOS	-89, -95
Shadowing deviation (σ) for both LOS, NLOS	3.15, 2.91

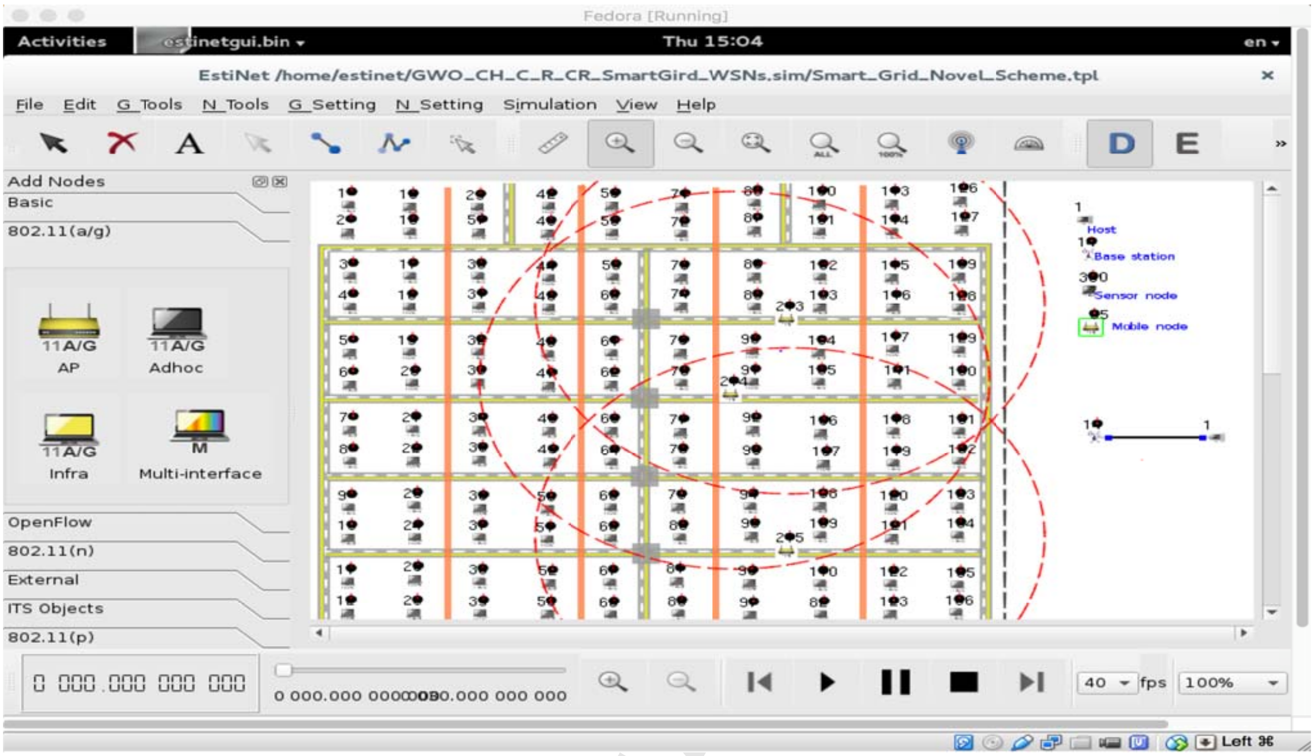


Fig.1 A view of the network model of MQRP scheme is shown in EstiNet9.0. Herein, it should be noted that the horizontal orange color lines are generating the same interference level as systems in the smart grid (see Section 5 for detail). Each red color dotted circle shows the communication range of a mobile sink in the smart grid. The tiny computer icons equipped with wireless communication capabilities are the sensor nodes having unique identity number between 1 and 300. The mechanical devices with numbers between 203 and 207 are the mobile nodes in the smart grid. The connected host and base station are represented by unique identify number 1 (see left side of the field) in the smart grid, while the black color solid line between the base station and a user shows the highly stable link connectivity in the network.

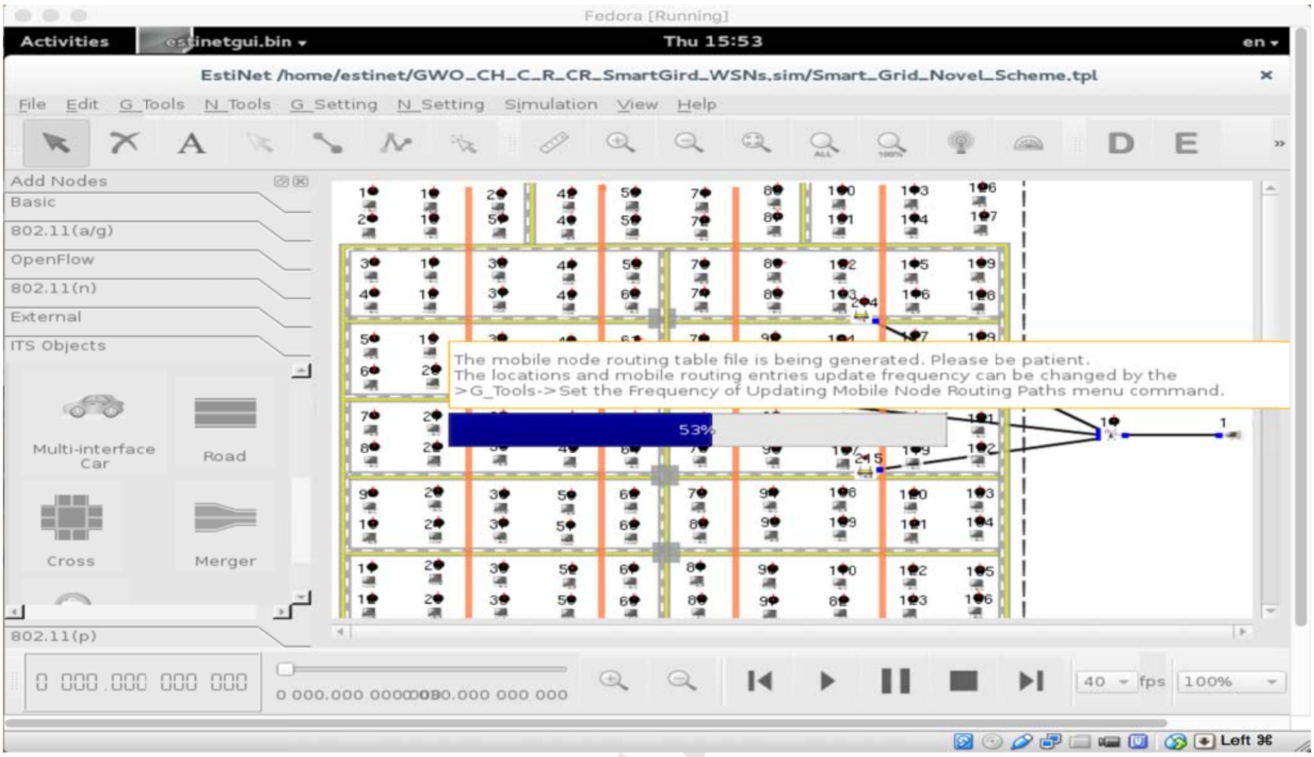


Fig.2 A view of the mobile sink updating its routing table is shown in EstiNet9.0. Here, it must be noted that each mobile sink is updating its routing table including, unique identity, distance information, residual energy and location information of the neighboring sensor nodes and mobile sinks in the field. In addition, each mobile sink periodically sends updated information of the neighboring sensor nodes and mobile sinks to the remote user via base station over highly stable links (black color solid lines) as shown above.

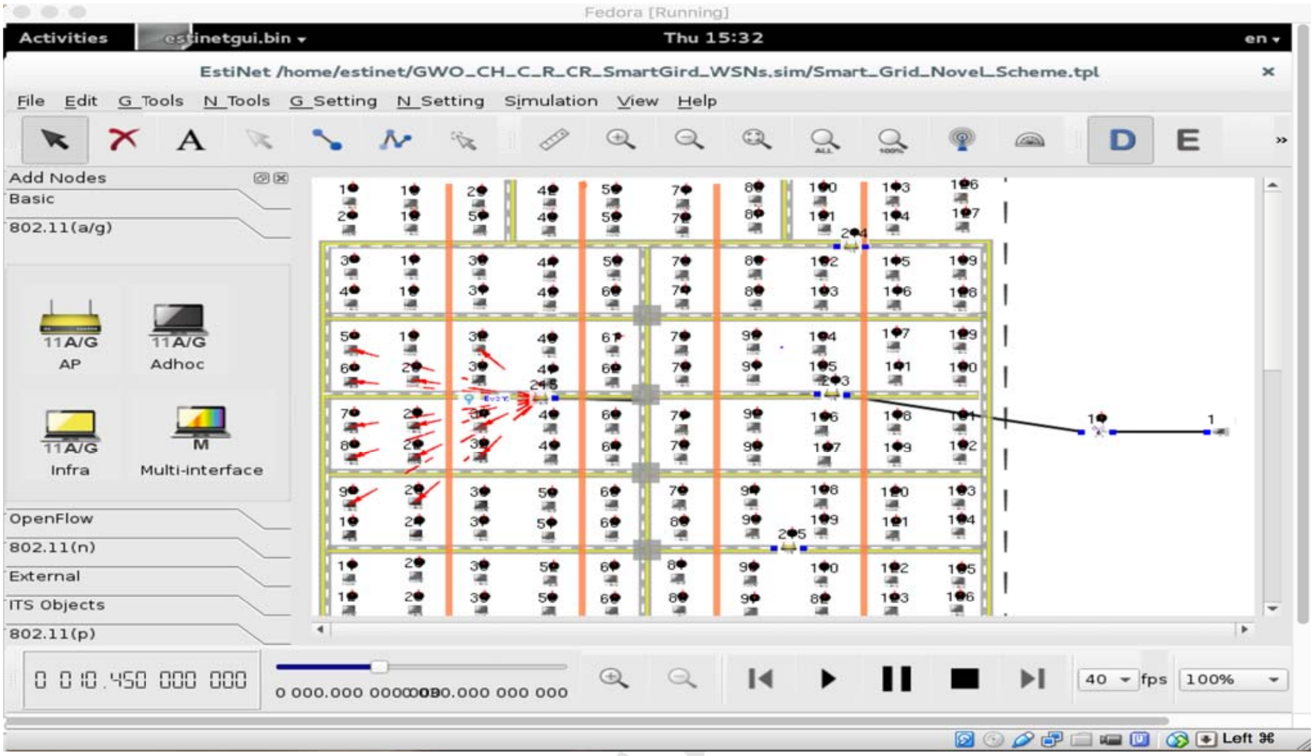
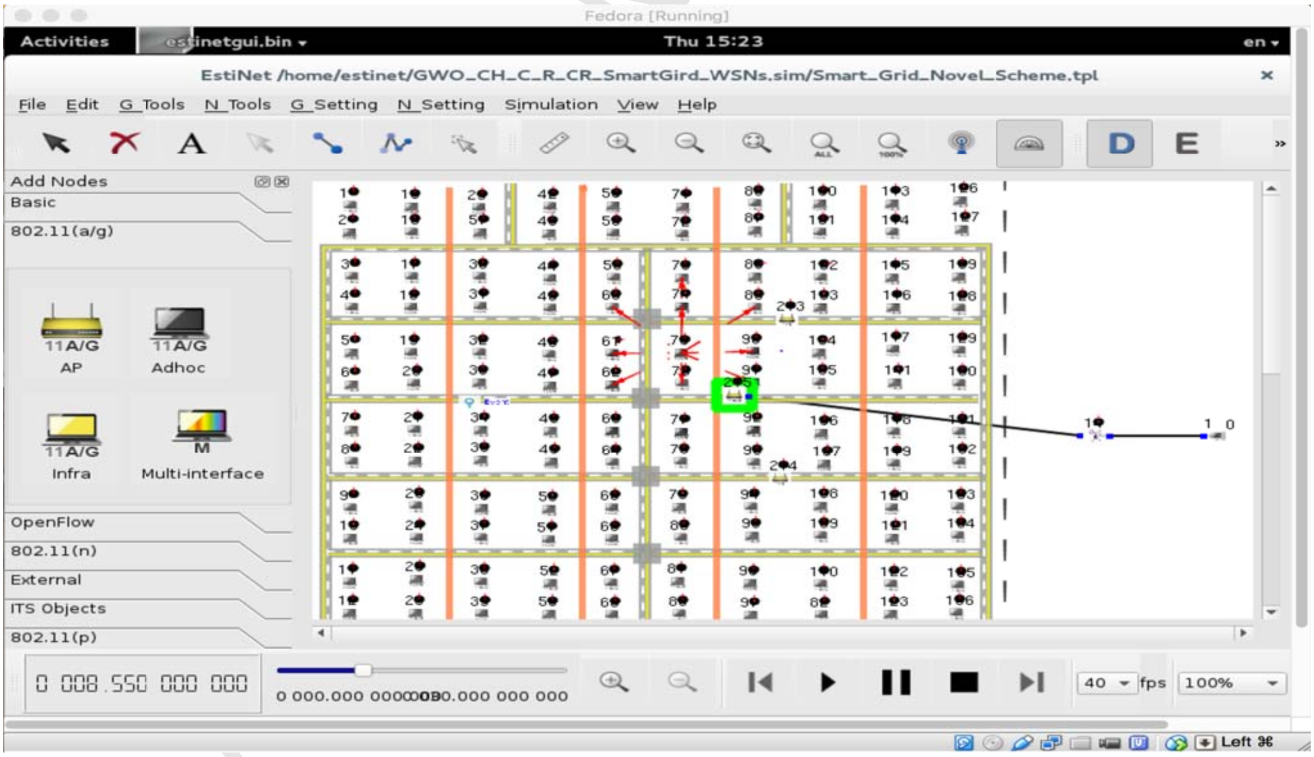

Fedora [Running]
Activities
estinetgui.bin
Thu 15:32
en
EstiNet /home/estinet/GWO_CH_C_R_CR_SmartGird_WSNs.sim/Smart_Grid_Novel_Scheme.tpl
File
Edit
G_Tools
N_Tools
G_Setting
N_Setting
Simulation
View
Help
Add Nodes
Basic
802.11(a/g)
11A/G
AP
11A/G
Adhoc
11A/G
Infra
Multi-interface
OpenFlow
802.11(n)
External
ITS Objects
802.11(p)
40
fps
100%

Fig.3 (a)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Activities
estinetgui.bin
Thu 15:23
en
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File
Edit
G_Tools
N_Tools
G_Setting
N_Setting
Simulation
View
Help
Add Nodes
Basic
802.11(a/g)
11A/G
AP
11A/G
Adhoc
11A/G
Infra
Multi-interface
OpenFlow
802.11(n)
External
ITS Objects
802.11(p)
40
fps
100%

Fig.3 (b)

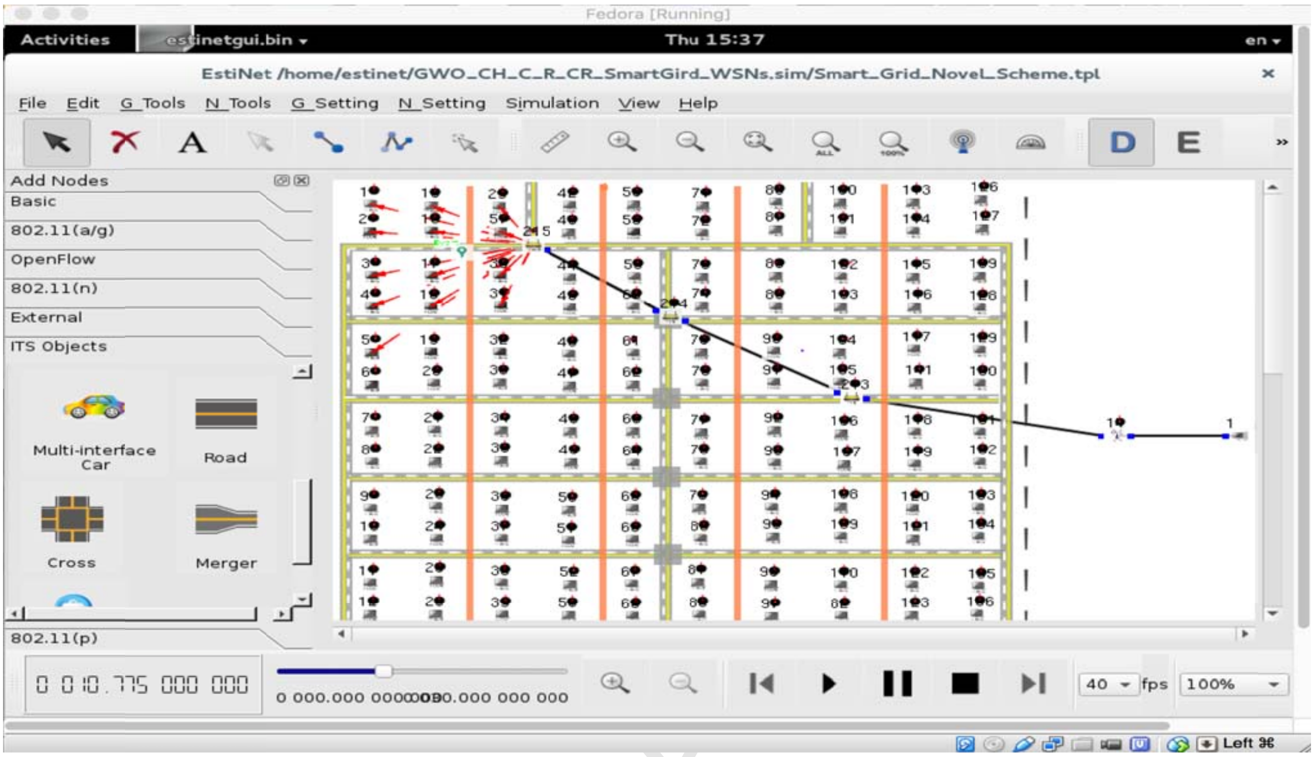

Fedora [Running]
Activities
estinetgui.bin
Thu 15:37
en
EstiNet /home/estinet/GWO_CH_C_R_CR_SmartGird_WSNs.sim/Smart_Grid_Novel_Scheme.tpl
File Edit G_Tools N_Tools G_Setting N_Setting Simulation View Help
Add Nodes
Basic
802.11(a/g)
OpenFlow
802.11(n)
External
ITS Objects
Multi-interface Car
Road
Cross
Merger
802.11(p)
0 000.000 000 000 0 000.000 000 000
40 fps 100%

Fig.3 (c)

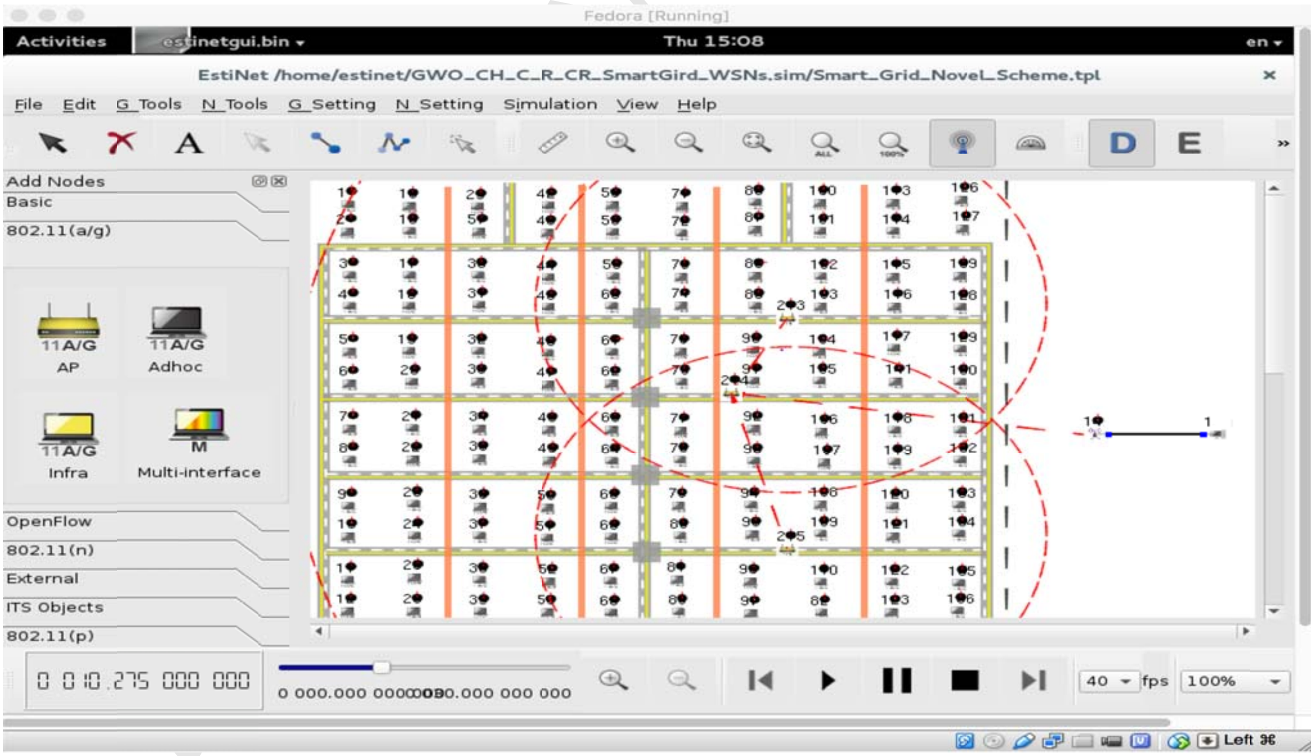

Fedora [Running]
Activities
estinetgui.bin
Thu 15:08
en
EstiNet /home/estinet/GWO_CH_C_R_CR_SmartGird_WSNs.sim/Smart_Grid_Novel_Scheme.tpl
File Edit G_Tools N_Tools G_Setting N_Setting Simulation View Help
Add Nodes
Basic
802.11(a/g)
11A/G AP
11A/G Adhoc
11A/G Infra
Multi-interface
OpenFlow
802.11(n)
External
ITS Objects
802.11(p)
0 000.000 000 000 0 000.000 000 000
40 fps 100%

Fig.3 (d)

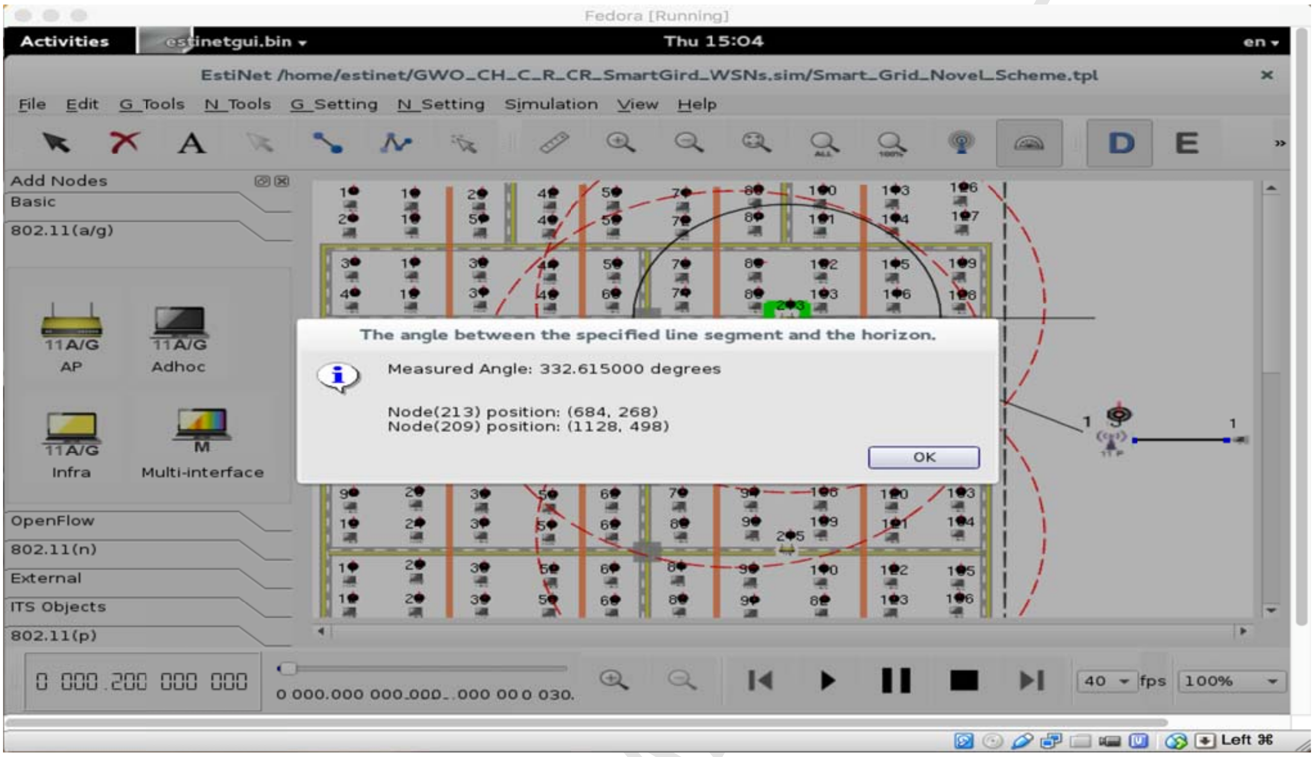

Fedora [Running]
Activities
estinetgui.bin
Thu 15:04
en
EstiNet /home/estinet/GWO_CH_C_R_CR_SmartGird_WSNs.sim/Smart_Grid_Novel_Scheme.tpl
File Edit G_Tools N_Tools G_Setting N_Setting Simulation View Help
Add Nodes
Basic
802.11(a/g)
11A/G AP
11A/G Adhoc
11A/G Infra
M Multi-interface
OpenFlow
802.11(n)
External
ITS Objects
802.11(p)
The angle between the specified line segment and the horizon.
Measured Angle: 332.615000 degrees
Node(213) position: (684, 268)
Node(209) position: (1128, 498)
OK
fps
100%
Left ⌘

Fig.3 (e)

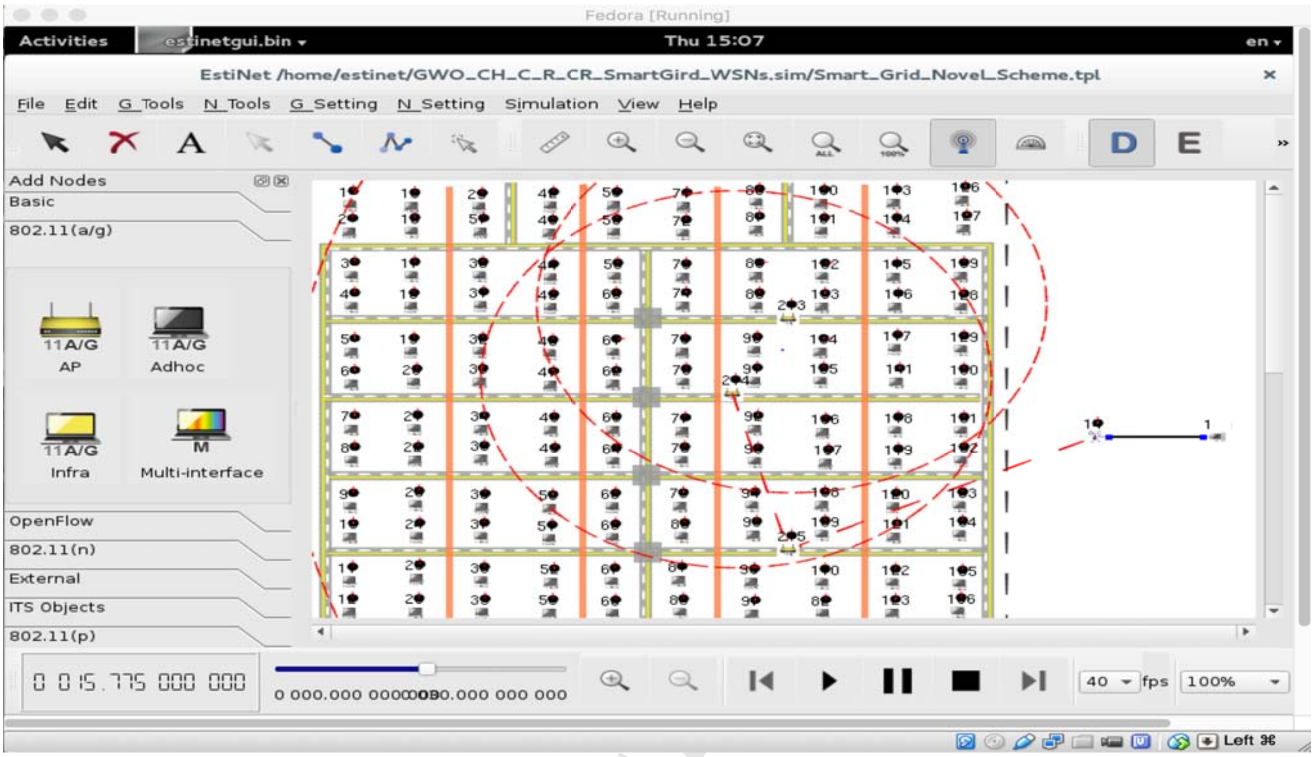


Fig.3 (f)

Fig.3 (a) shows that a mobile sink is limited broadcasting information of its arrival to a set of sensor nodes in a sub-area. Fig.3 (b) displays that a sensor node is broadcasting information to its one-hop neighboring sensor nodes and a mobile sink after receiving data from its member sensor nodes directly sending to a BS. Fig.3(c) illustrates that after receiving information from a set of sensor nodes, a mobile sink forwards the information to a BS via multi-hop mobile relay hops in the network. Fig.3 (d) indicates that a mobile sink is broadcasting its information to its neighboring mobile sink in the network. Fig.3 (e) expresses that a mobile sink is updating its location information and informing to the BS. Fig.3 (f) demonstrates that a mobile sink after each sharing information replying to its associated mobile sink via a reply message to ensure that a packet has been received successfully.

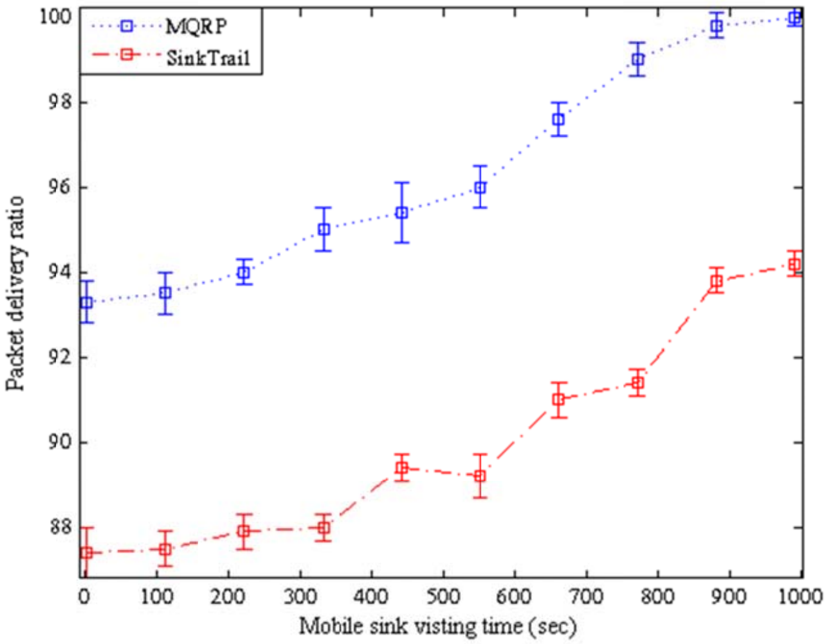

MQRP
SinkTrail
Packet delivery ratio
Mobile sink visting time (sec)
100
98
96
94
92
90
88
0
100
200
300
400
500
600
700
800
900
1000

Fig.4 (a)

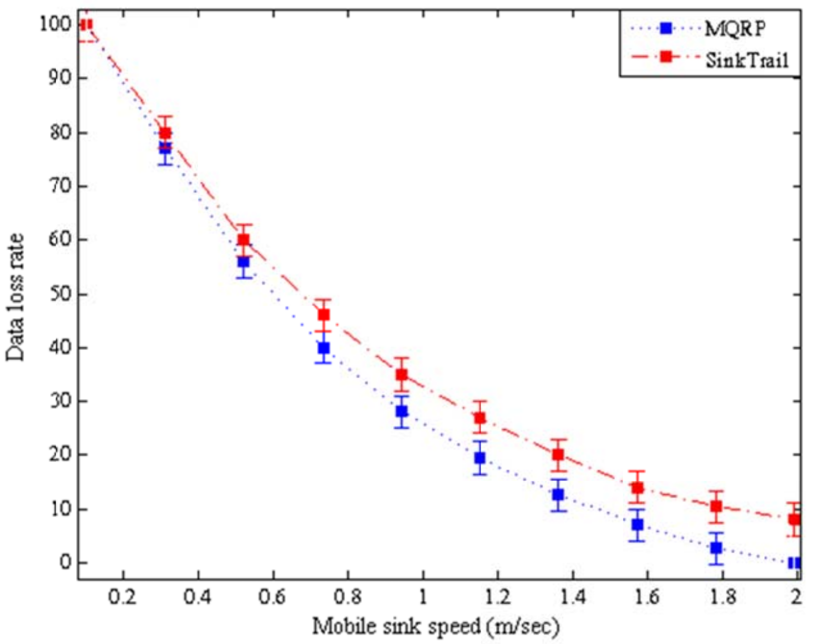
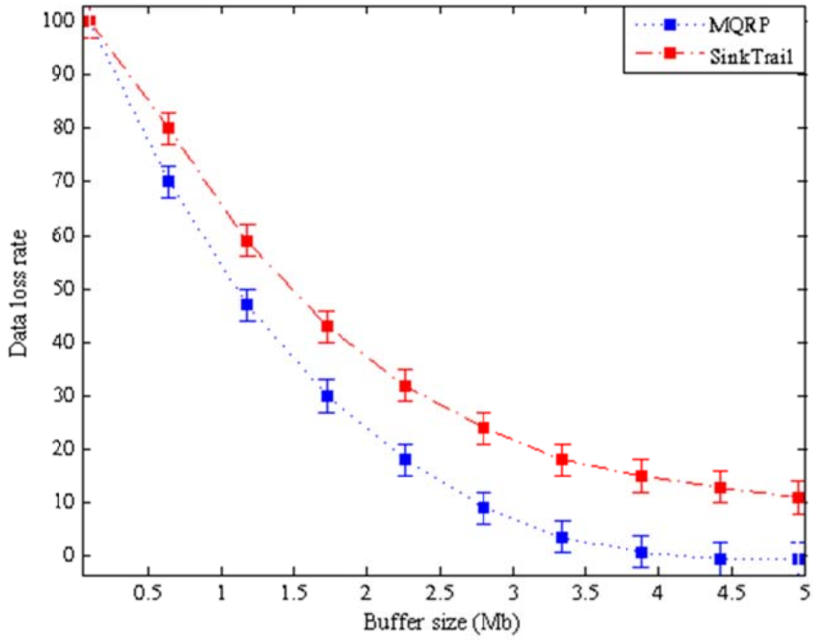
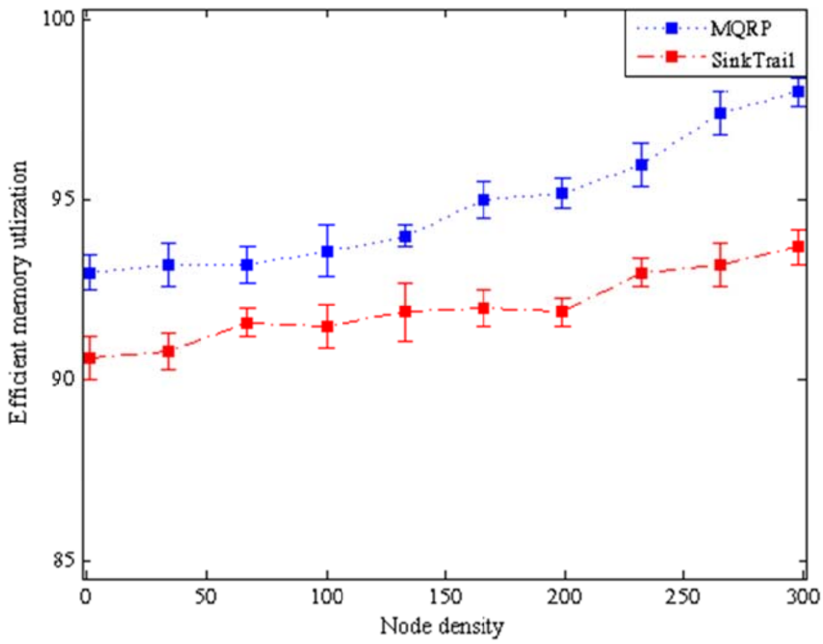

MQRP
SinkTrail
Data loss rate
Mobile sink speed (m/sec)
100
90
80
70
60
50
40
30
20
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Fig.4 (b)



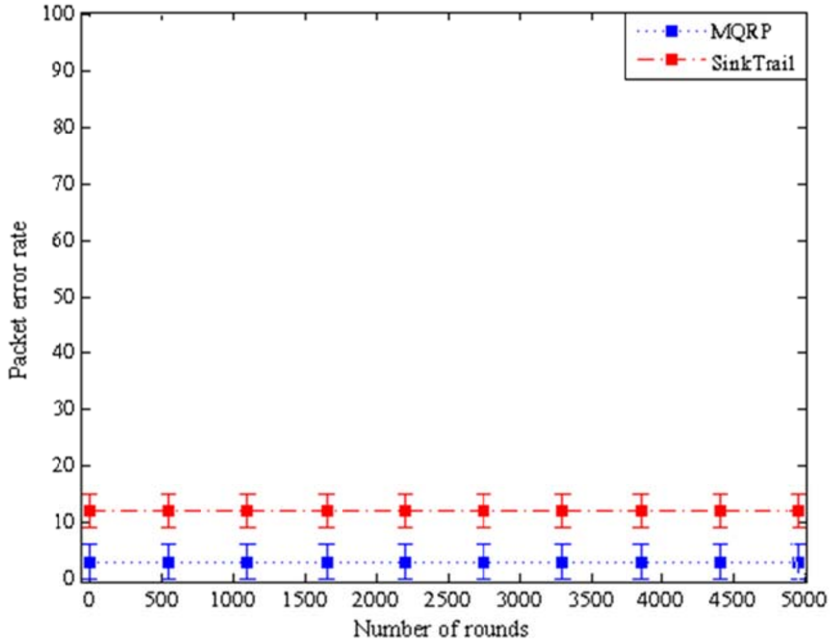
MQRP
SinkTrail
Data loss rate
Buffer size (Mb)
100
90
80
70
60
50
40
30
20
10
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Fig.4 (c)



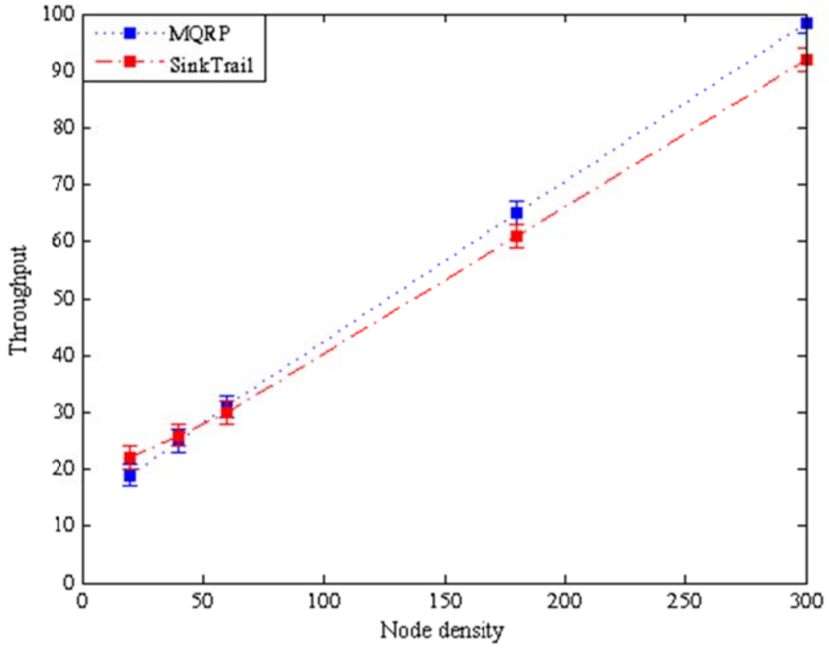
MQRP
SinkTrail
Efficient memory utlization
Node density
100
95
90
85
0
50
100
150
200
250
300

Fig.4 (d)



MQRP
SinkTrail
Packet error rate
Number of rounds
0
10
20
30
40
50
60
70
80
90
100
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Fig.4 (e)



MQRP
SinkTrail
Throughput
Node density
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300

Fig.4 (f)

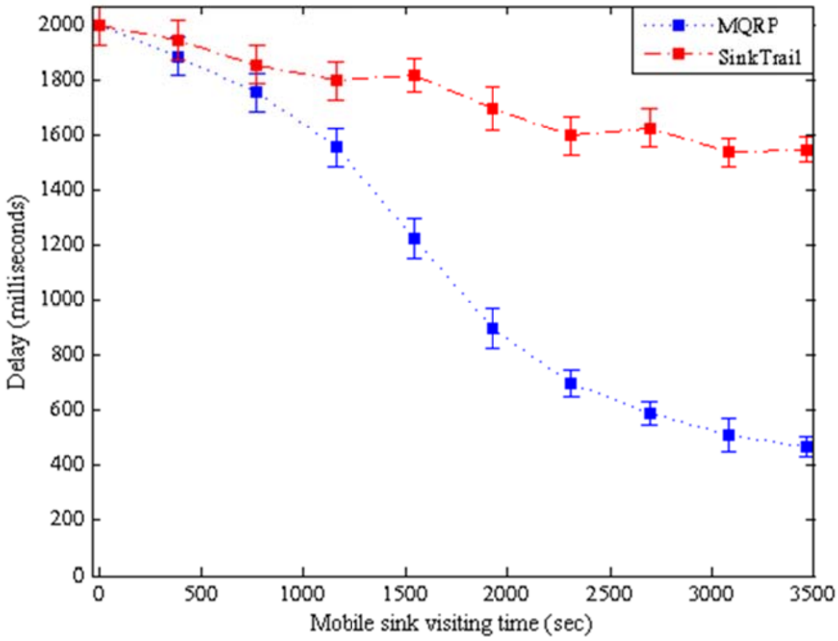

MQRP
SinkTrail
Delay (milliseconds)
Mobile sink visiting time (sec)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
500
1500
2500
3000
3500

Fig.4 (g)

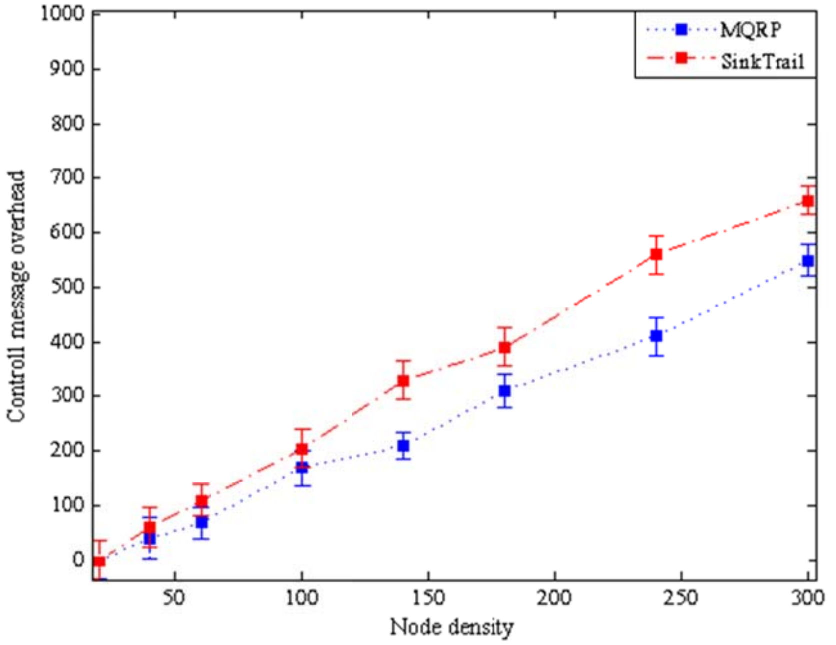

MQRP
SinkTrail
Controll message overhead
Node density
0
100
200
300
400
500
600
700
800
900
1000
50
150
250

Fig.4 (h)

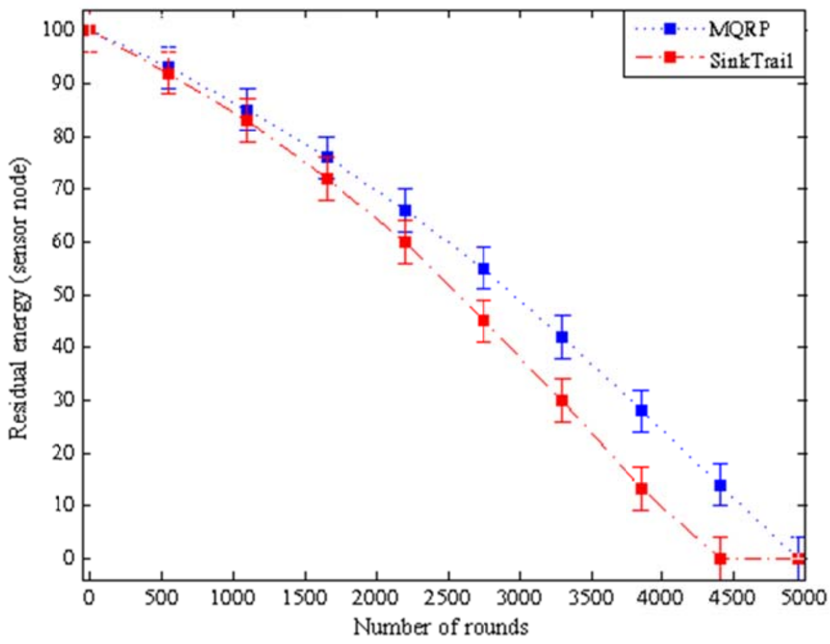


Fig.4 (i)

Fig.4 (a) shows the packet delivery ratio vs mobile sink visiting time in seconds. Fig.4 (b) displays the data loss rate vs speed of the mobile sink in meter per second. Fig.4(c) illustrates the data loss rate vs sensor node buffer size in megabit. Fig.4 (d) indicates the efficient memory utilization vs node density. Fig.4 (e) shows the packet error rate vs number of rounds. Fig.4 (f) demonstrates the throughput vs node density. Fig.4 (g) expresses the delay in milliseconds vs mobile sink visiting time in seconds. Fig.4 (h) presents the control message overhead vs node density, and finally Fig.4 (i) shows the residual energy of sensor nodes vs number of rounds for both MQRP and SinkTrail data collection schemes in the network.

Author's Biography

Muhammad Faheem received the B.Sc. Computer Engineering degree in 2010 from the Department of Computer Engineering at the University College of Engineering & Technology, Bahauddin Zakariya University Multan, Pakistan. In 2012, he received an MS degree in Computer Science from the Faculty of Computer Science and Information System at Universiti Teknologi Malaysia. Currently, he is a Ph.D. student at Abdullah Gul University, Kayseri, Turkey. His research interest includes the areas of smart grid communications, energy harvesting, underwater acoustic communications, cognitive radio sensor networks, and information storage and retrieval architecture from the sensor memory. Mr. Faheem has authored several papers in refereed journals and has been serving as a reviewer to numerous Journals, such as Journal of network and computer applications, Ad-hoc networks, Australian journal of electrical engineering, Computer standards and interfaces and IEEE Access.

Vehbi Cagri Gungor received his B.S. and M.S. degrees in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey, in 2001 and 2003, respectively. He received his Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta, GA, USA, in 2007. Currently, he is an Associate Professor and Chair of Computer Engineering Department, Abdullah Gul University (AGU), Kayseri, Turkey. His current research interests are in smart grid communications, machine-to-machine communications, next-generation wireless networks, wireless ad hoc and sensor networks, cognitive radio networks. Dr. Gungor has authored more than 80 papers in refereed journals and international conference proceedings and has been serving as an Associate Editor of prestigious journals, such as for IEEE Transactions on Industrial Electronics and Ad Hoc Networks (Elsevier). He is also the recipient of the Distinguished Young Scientist Award (The Scientific and Technological Research Council of Turkey (TUBITAK)) in 2017, Distinguished Young Scientist Award (BAGEP) in 2016, Turkish Academy of Sciences Distinguished Young Scientist Award (TUBA-GEBIP) in 2014, IEEE Trans. on Industrial Informatics Best Paper Award in 2012, the European Union FP7 Marie Curie IRG Award in 2009, AVEA Research Grant Awards in 2013 and 2014, Turk Telekom Research Grant Awards in 2010 and 2012, and the San-Tez Project Awards supported by Alcatel-Lucent, and the Turkish Ministry of Science, Industry and Technology in 2010. Importantly, Dr. Gungor's recent paper on smart grid communications has been ranked 8th in the Top Accessed Article List in the IEEE Xplore as of 2012. Email: cagri.gungor@agu.edu.tr

Highlights

In this paper, we propose a low-complexity multi mobile sinks-based QoS-aware data gathering protocol and formulate the problem as mixed integer linear programming (MILP) for SG applications.

The developed scheme follows a hybrid mobility pattern, where initially sinks move in a strictly deterministic manner and then based on self-learning, that attempts to significantly improve region-based coverage issues, avoids nodes buffer overflow time and reduce latency by scheduling the mobile sinks movement in the network. Moreover, the designed scheme also considers aggressive data collection strategy by enabling multi-hop data collection for the sensor nodes away from the mobile sinks. It effectively reduces long distance data transmission energy consumption in a greedy manner for SG applications in the network. The designed scheme during multihop data forwarding process preserves high link quality among sensor nodes as well as to the mobile sinks for minimizing corrupted/invalid and data packets loss in the network. In addition, the designed scheme by using a combination of mobile sinks distributes data traffic and energy consumption load evenly with lower bounded latency in a greedy manner for SG applications. In sum, the designed scheme cuts down total energy consumption under the condition that the total amount of QoS data collected by the evenly distributed mobile sinks is maximized in the smart grid environments.

In the end, we conducted simulation experiments using a network simulation tool called EstiNet9.0. The obtained results from the simulations study validate the effectiveness of the proposed scheme in terms of packet delivery ratio, packet error rate, latency, throughput, memory utilization, control message overhead, and energy efficiency.