Software Defined Communication Framework for Smart Grid to Meet Energy Demands in Smart Cities

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***Abstract*—In smart cities, the electricity is an essential component since it preserves a certain level of residents' life quality and provisions the entire spectrum of their economic activities. Thus, a smart way is essential to develop cities without disregarding energy issues. In this scope, the smart grid paradigm offers power supply in an efficient, sustainable and economical manner with minimal impact on the environment and can meet the future energy demands. However, real-time monitoring and control of the smart grid (SG) for continuous and quality-aware power supply in smart cities (SCs) is challenging and requires an advanced quality of service (QoS)-aware communication framework. In this context, this research aims to present a novel data-gathering scheme by using the Internet of software-defined mobile sinks (SDMSs) and wireless sensor networks (WSNs) in the smart grid. The extensive simulation results conducted through the EstiNet9.0 indicate that the designed scheme outperforms existing approaches and achieves its defined goals for events-drive applications in the SG.**

***Index Terms*— Internet of thing, smart cities, smart grid, mobile sink, wireless sensor network.**

I. Introduction

The smart cities are totally reliant on electricity to power zillions of connected micro and macro modern devices for providing quality of life to citizens. These devices in sum consume a huge amount of energy, which is expected to increase drastically in the future. Such as increasing energy consumption lead to existing centralized controlled power grids (PGs) instability. Therefore, there are several issues related to existing aging PGs such as being unreliable, low power quality, low customer satisfaction and too high electricity prices. Hence, it is crucial to enhance existing power generation plants, and distribution capabilities for dynamic power delivery in the smart energy cities (SECs) [1]. To this end, a new approach widely known as the smart grid has gained increasing attention with the potential to improve the reliability and sustainability of the electricity production and distribution in the SECs. Therefore, the SG is considered as the backbone of the smart energy city with the potential to significantly improve dynamic energy management by integrating renewable energy sources into existing PGs [2]. In the overall smart grid framework, the communication technologies (CTs) perform a major role by connecting various types of cyber-physical systems (CPSs). Consequently, the fundamental objective of the Internet of Thing (IoT) technology is to provide advanced connectivity between machines and humans for enabling a real-time transfer of knowledge between SG and SECs. Currently, wireless and wired communication technologies are used to collect information from different cyber-physical systems in the SG [3]. However, compared to wired solutions, the wireless communication technologies (WCTs) have a number of merits such as low-cost deployment, architecture flexibility and long-distance communication. In this context, industrial wireless sensor network (IWSN) is a viable technology for various SG applications such as home energy management, distribution management and several others. In addition, the software-defined mobile sink (SDMS)-based data gathering in WSNs has drawn enormous attention in recent years in the SG [4]. The SDMS based data gathering technique offers improved network control and programmability by separating the control and data planes based on vendor's application-specific devices in the smart grid. Recently, some WSNs-based data collection schemes exist in the literature. For example, some authors try to solve network delay and packet delivery ratio in [5] while others try to address the problem of energy efficiency and packet error rates in [3]. In addition, some studies are focusing on the network stability [6], reliability [7], and throughput [2] [8] in the smart grid. However, they are not fully capable of providing the QoS-aware data gathering in SG to supply consistent power supply in the smart cities. To this end, this research aims to present a novel opportunistic data gathering mechanism by using the Internet of SDMSs and WSNs to monitor SG events for quality energy management in the SECs. The simulations result obtained through the network simulation tool EstiNet9.0 reveal that the designed scheme compared to existing studies significantly improves the ratio of data delivery and reduces the corrupted data packets, memory overflow, latency and energy consumption to prolong the network lifetime (NLT).

The remainder of this work is structured as follow. The proposed scheme and path loss and energy consumption models are presented in Section II and Section III, respectively. Section IV presents simulation settings, metrics and discusses the performance analysis in detail. Finally, the summary of the research and solid potential research guidelines are given in conclusion Section V.

II. Proposed Software Defined Mobile Sink And WSNs-Based Data Gatering Protocol (SDRP)

A. Network Model and Assumptions

In the proposed network model, the sensor nodes (SNs), SDMSs and a base station (BS) are deployed for events monitoring purposes in a specific 2D region, i.e., a 320kV smart grid. The randomly deployed static SNs know their

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location in the SG. The deployed SNs are same in term of initial energy and data processing capabilities. The SNs and mobile sinks (MSs) are aware of their initial locations, which can be computed by using a localization mechanism presented in [9]. In addition, all the SNs have same sensing and communication radius, and communication is only successful if the neighboring SNs are within the transmission range that means there is a link between two SNs in the network. Each mobile sink is embedded with an OpenFlow switch, and two wireless transmissions interfaces are installed for short and long-distance communication between SNs and MSs, MS and neighboring MSs, and MS and BS in the network. The SDMSs are rich in computing resources and unlimited energy supply at the depot. The paths on the defined roadmap are connected on which the mobile sinks can travel in the subregions and can stop at any point refers to a sojourn location on the roads in the network. It is also assumed that each mobile sink completes its tour of data collection per round or runs out of energy must return to the depot for recharging or replacing the battery. It is assumed that the SDN controller is embedded with the BS and rich in memory, computing resources, and energy supply. We assume one of the data transfer technologies, such as 4G (Fourth Generation) or Microwave, which enables long-distance data transmission with high data rates between MSs and BS. To provide highly stable connectivity to the remote user/s, we also assume long-distance data transfer technologies such as 5G (Fifth Generation) or Satellite communication because of their high data rates and coverage in the network. Furthermore, it is assumed that the packet transmission delay of the MSs to BS and the BS to remote user/s is negligible in the smart grid. Lastly, to avoid packet collision the transmitted signals from each SN and MS follows a carrier sense multiple access (CSMA) technique in the SG.

B. Design of Software-defined architecture in SDRP

In the proposed scheme, the whole software-defined networking architecture for MSs has been divided into two layers, namely the control layer and the data layer in the smart grid. The control layer consists of a single centralized SDN controller aiming to perform necessary actions based on the user-defined rules in the smart grid. The SDN controller enables various smart grid events monitoring applications to run on top of it, which can be configured and modified in the network. The fundamental purpose of the SDN controller is to update network services and provide a flow control messages to each switch embedded on the mobile sink. Thus, the use of a centralized SDN control enhances the efficient control of the MSs and sensor network as it provides a global view of the network. The mobile sinks and sensor nodes are the key elements of the data plane. In the data plane, each mobile sink is embedded with a switch consists of a software implemented OpenFlow protocol. The primary purpose of an OpenFlow protocol is to enable communication between the SDN controller and MSs in the smart grid environments. Thus, it provides a standardized way of communication between mobile sinks and the SDN controller by monitoring the topology in a real-time in the smart grid. The MS embedded with OpenFlow switch is comprised of a flow table (FT) that is represented by a triplet < header, counter, actions >. In which the header matching pattern is used to identify the packets, the counter is an entry matching precedence, and the action function performs appropriate operations on the matched packet in the smart grid. The header pattern usually comprises an input port number, unique identity number, source and destination address in the network. In the matching field, all packets according to the attributes belong to the same flow only if they match the same matching pattern in the network. The action field describes how the flow on each flow entry must process in a switch in the smart grid. The action field holds common operations, such as modify the packet header, a specific output port, drop the packet, forward the packet and broadcast the packet in the network. In the action field, usually, an action of a specified rule is applied to each packet of the corresponding flow in the smart grid. In a scenario, if multiple matching patterns match a packet then only the actions with the highest priority are applied to the SNs or MSs. Therefore, the list of defined rules is stored in an appropriate form with decreasing priority in the flow table queue. This mechanism offers an instant reaction to the high priority rules so that halt and delay in the processing can be avoided in the network. Upon receiving a packet, each switch searchers its header information in the FT. Then, it performs the related action only if a flow matches with an entry which is stored in the FT. Otherwise, the switch at first insert the packets into a temporary unresolved buffer queue and then forwards it to the SDN controller for appropriate rules or actions. Upon receiving the packet, the controller identifies the running smart grid application flow, defines appropriate actions and installing them on the associated switch flow table via an OpenFlow protocol. Thus, all control functionalities from the communication devices are extracted and placed in a logically centralized SDN controller, which helps the remote user/s to change the network behavior and easily implement new actions according to the application requirements. In proposed scheme, the whole working mechanism consists of three main layers, namely control layer, data layer, and application layer for smart grid applications. Consequently, the whole working mechanism undergoes two main phases. The first one is to select rendezvous points and setup routes for SNs in a way that meets application specific service guarantees in the SG. The second one is to collect data from SNs in both proactive and passive manner through the MSs in the network. Thus, the SDN controller is responsible to ensure that the traffic is routed over a feasible path between SNs and MSs under given QoS requirements in the SG. The entire process of route constructions and data gathering is divided into the following sections. Remember that, we use the terms switch embedded on the mobile, mobile switch and mobile sink alternatively in the following sections of this paper.

C. Mobile Sinks Path Planning and Network Inilization

The mobile sinks collect sensed data from SNs and is modeled as the traveling salesman problem (TSP) problem in the SG. [10]. The generalized form of the TSP is also known as the vehicle routing problem (VRP) used to find a set of optimal routes for multiple vehicles located at various locations in the network. The vehicle routing problem plans a set of approximately optimal routes for multiple mobile sinks in each specific region in the SG. Therefore, in the designed scheme, the paths planning problem is modeled as the VRP, which minimizes the distance traveled by all the mobile sinks in the SG. In sum, for each mobile sink embedded with a moving vehicle has four choices to move on the railroad like paths, including direction upside, downside, left side and right side in the smart grid. The network initialization process basically uses a package of three types of messages, including initialization request (IREQ), reply request (RREQ) and acknowledgment (ACK) in the SG. In the beginning, the SDN controller based on the user instructions sends an IREQ message to each mobile sink via an OpenFlow protocol in order to start an initialization process in the smart grid. After receiving the IREQ message, each mobile sink moves with constant speed along a predetermined trajectory and broadcasts a network IREQ message by adjusting its radio communication range in a particular part of the network. The main purpose of the IREQ message is to allow SNs to compute the mobile sink trajectory and discover neighboring SNs in the network. Consequently, an IREQ message contains a mobile sink identity, location information, current speed and time of packet transmission. The sensor nodes after receiving the messages synchronize their local time by using mobile sink time and locate the trajectory of the mobile sink. Then, each sensor node establishes its MS trajectory table in the smart grid. Each time, the SN accesses the vacant wireless channel by using CSMA mechanism during sending information towards the MS. This mechanism decreases the number of packets collision by avoiding the SNs to simultaneously access the wireless channels for sharing information in the network. This whole procedure repeats until each SN in the smart grid has most updated MSs information stored in its routing table. Later, each SN that received the IREQ message sends an ACK message to the sender MS, which ensures the guaranteed delivery of the message. Finally, the received information from SNs is delivered to the SDN controller from the MSs through an OpenFlow agent.

D. Rendezvous Points Selection

In a large-scale smart grid, visiting every SN by the mobile sink is impractical since it experiences an excessive delay because of the longer path length and therefore may not be a good option for events driven applications. In this context, a potential solution is to find the minimum number of rendezvous points, i.e., sojourn locations in each region and permits each mobile sink to gather data from SNs at the rendezvous points only through short distance single-hop communication over highly reliable links in the SG. Therefore, in the proposed mechanism, a predefined number of sojourn locations based on the SNs position are selected in each subregion of the deployed network. Consequently, at this stage, the SDN controller has all the recent information about the MSs and SNs in the network. The SDN controller runs a package of rendezvous point's selection in each subregion in the network. During rendezvous point's process, the SDN controller computes the weight value of each SN based on its residual energy, link quality, location and the minimum distance between SNs and MSs in the smart grid. Then, it selects a set of a predefined number of one-hop SNs as rendezvous points or sojourn locations based on their maximum weight values in each subregion in the SG. After choosing a set of rendezvous sensor nodes (RSNs), the SDN controller limited broadcasts a rendezvous appointment (RAREQ) request message, which floats through the associated mobile sink and delivers to each selected RSNs in the smart grid. This limited broadcasting of RAREQ message to a set of specific RSNs reduces the problems such as interference, signal collision and redundancy in the network. After receiving the RAREQ message, each RSN replies via RREQ to the SDN controller through an associated mobile sink. The excessive number of sojourn positions may increase the waiting latency of the MSs for gathering data in the SG. Therefore, the proposed mechanism avoids an excessive number of SNs appointments as rendezvous points in each subregion in the smart grid. Now, each appointed RSN knows the associated mobile sink in the network. Consequently, each RSN and MS updates its location and neighboring information table in the smart grid. Upon receiving the RREQ message, the SDN controller defines data flow rules for each RSN and mobile sink. These rules and actions are forwarded through an OpenFlow agent to the associated mobile sink where they are saved in the flow table with decreasing priority.

E. Data Gathering Modes

The data collection process consists of several rounds. In every data collection round, each SN monitors its vicinity and stores sensed information in the limited memory. In the beginning, the mobile sinks traverse with a constant speed and limited broadcast a polling (PREQ) request message to their associated SNs located in different regions in the smart grid. Upon receiving the PREQ message, each RSN computes the current location and distance of the MS in the SG. The RSNs continuously monitor the communication range of the MS and time when it enters and leaves the region. Thus, each RSN observes the mobile sink movement and updates its location table with the recent location information and time of staying in the communication range in the smart grid. Consequently, each SN after receiving the PREQ message starts to forward it's sensed data to the rendezvous point using short distance communication in the SG. The SNs always add a unique timestamp on each data packet to record the effective time in the SG. Thus, the whole sensed information from the source node is routed towards the rendezvous points. As soon as data is received, the RSN directly uploads sensed information to the mobile sink only if its communication range is higher than the measured distance to the mobile sink. The mobile sink stays for a predefined amount of time at each sojourn location for gathering data from RSNs and ensures that entire information has been transferred successfully. Herein, there are two possibilities here either the mobile sink will arrive or already has visited the RSN for data collection. The information of the mobile sink location is obtained based on the arrival and departure information saved in the location table of every rendezvous sensor in a greedy manner. Consequently, a rendezvous SN based on its previous mobile sink history information starts negotiating with its neighboring RSNs in order to convey messages to the mobile sink. As soon as, the cache emergency SNs send their sensed data to their associated RSNs in the smart grid. The RSNs after receiving the data, regardless the mobile sink has not yet reached send the received information towards the neighboring RSNs in the direction of the mobile sink. Then, each receiving RSN forwards the message again to the nearest rendezvous sensor that is nearer to the MS. This process repeats until the data is delivered to the associated mobile sink in a greedy manner. Thus, the whole information is uploaded to the closest MS in a proactive manner. Similarly, if the cache emergence occurs at the RSN then it also sends its data to neighboring RSNs towards the MS regardless it has not yet reached. Otherwise, it uploads the information directly to the MS in a case if the MS is in the communication range. After gathering data, the flows are matched and appropriate actions are performed based on the rules defined in the OpenFlow switch. Then, the mobile after receiving the data from RSNs moves to another sojourn location in the network. During the data transmission process, each relay RSN and MS after successfully receiving the packets replies via an ACK message in the network. After a predefined number of rounds, each mobile sink starts to moves based on its previous history information for events information collection in the SG. This self-learning based mobile sink movement extremely reduces the information collection latency in the SG. Thus, the whole information is uploaded to the mobile sinks in a predefined timespan in a real-time fashion in the SG. In this way, all the MSs visit the RSNs and complete their single data collection round. Thus, designed scheme reduces the data loss rate by avoiding excessive sensor's memory overflow problems in the network. Similarly, the time emergency data from SNs or RSNs is uploaded towards the mobile sink before the packet's deadline expires. Throughout the data forwarding process, each sender SN or RSN receives the ACK messages from data receiving SNs or RSNs in the SG.

F. Rendezvous Points Re-selection

The energy of RSNs is exhausted prematurely due to relaying a huge volume of neighboring SNs information in the SG. Therefore, it is important that an RSN goes beyond the predefined threshold energy limit must be replaced with the new one in order to balance the energy consumption load in the network. To do so, if the energy level of an RSN becomes lower than the defined threshold energy level then it sends a low energy LEREQ message to the associated mobile sink. Upon receiving the LEREQ message, the flow of the RSN is identified in the switch and forwards to the SDN controller via an OpenFlow agent. As soon as the LEREQ message is delivered, the control appoints a new RSN based on its high weight since it already has recent information of the RSNs in the network. Herein, it is also possible that more than one SN have the same weight value in a subregion in the network. In that case, an RSN is appointed opportunistically in a subregion in the SG. After selection, the rendezvous point appointment RAREQ message is forwarded to the switch and delivered to the new RSN in the network. Upon receiving the RAREQ message, the new RSN sends an ACK message to the associated mobile sink. After receiving the ACK message, the rules and necessary actions are defined by the SDN controller and stored in the corresponding switch FT with decreasing priority.

III. Performance Evaluation

The path loss model numerically described in Eq.1 is used in our simulation studies [11].

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta log_{10}\frac{d}{d_0} - X_\sigma - P_\eta \quad (1)$$

While the energy consumption (E_c) model numerically described in Eqs.2 to 4 is used in our simulation studies.

$$E_{T_x}(K,d) = E_{elec} \times K + E_{amp} \times K \times d^2 \quad < d_0 \quad (2)$$

$$E_{T_x}(K,d) = E_{elec} \times K + E_{amp} \times K \times d^4 \quad \geq d_0 \quad (3)$$

$$E_{R_x}(K) = E_{elec} \times K \quad (4)$$

in which E_{T_x}, E_{R_x}, E_{elec}, E_{amp}, K, d and d_0 are, the data packets transmitting energy consumption, the data packets receiving energy consumption, the circuitry energy consumption of receiving or transmitting data packets, the constant signal amplifier coefficient, the number of bits, the physical distance between SNs and MSs, and the threshold physical distance depends on the communication radius of the SNs in the SG. We evaluate the performance of SDRP scheme against the well known mobile sink-based data gathering protocol called VELCT [5] through the discrete-event simulation tool named EstiNet9.0. In fact, the performance of both data gathering schemes is measured in the smart grid environment by using the metrics such as packet delivery ratio, delay, throughput and energy consumption in the SG. In our simulation, we consider a 320kV outdoor PG station with area 1000(length) × 900(width) meters containing 5 software-defined mobile sinks and 300 sensor nodes. The maximum velocity of each mobile sink is set to 2.35meters (m)/ seconds (sec). A smart grid consists of systems, subsystem, and electric poles with numbers 25, 77 and 130, respectively. The initial energy of each MS and SN were set to 10kilojoules (kJ) and 4 joules (J) respectively. In the SG, each sensor node is embedded with physical layer standard IEEE802.11g with a maximum communication range of 70m and data rates up to 256kilobits per second (kbps). In addition, the values of data packet size and data aggregation energy consumptions were set to 47 bytes and 0.018 watts (W). During network operations, each sensor node observes the smart grid events and stored data in its memory of maximum size 5Megabit (Mb). During conveying sensor data, the maximum amount of energy consumed for transmitting and receiving information between SNs is set to 0.97W and 0.15W in the network. In highly dynamic topologies, the values of ideal listening and sleeping power were set to 0.015W and 3×10^{-6} W. The value of path loss component (n), noise floor and shadowing deviation (σ) were set between 2.25 and 3.25, -85 and -90, and 3.01 and 2.8 for both line of sight and non-line of sight in the SG. Finally, we assumed 53 sets of simulations in order to provide consistent results in the network. The experimental facts show that the data gathering rate varies and highly depend on the mobile sink speeds between 0.1 meters/second (m/s) and 2.5m/s in both routing schemes as shown in Figure 1 (a). It clearly show that the mobile sink realizes a success rate of delivering data around 97% in SDRP and 92% in VELCT in the SG. In general, the least required speed of each MS for data collection in the different subregion is lower in SDRP in the SG. However, it is just greater than a predefined value so that the buffer overflow of the SNs located in a region can be

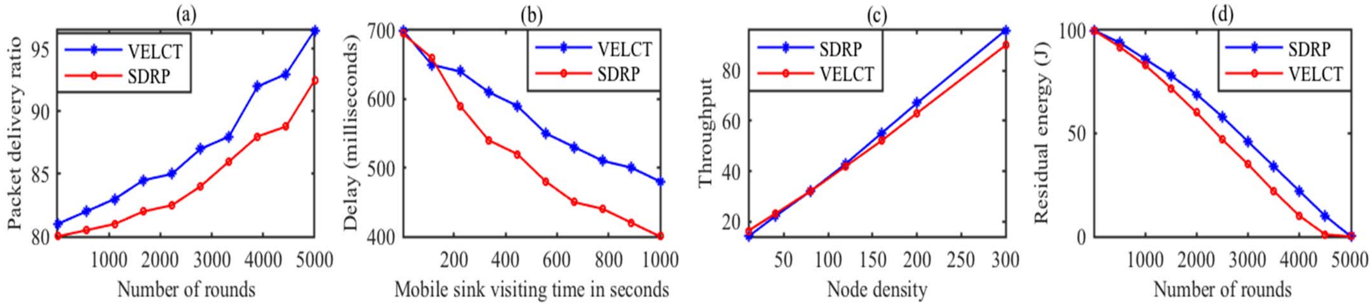

Fig.1 (a) shows the packet delivery ratio vs number of rounds (b) indicates the delay vs time in seconds (c) shows the network throughput vs node density and (c) illustrates the residual energy vs number of rounds in the network.

avoided by visiting them in the SG. Therefore, in SDRP the data loss rate occurs due to buffer overflow is lower since data is gathered from the cache emergence SNs within a predefined amount of time in the SG. Moreover, this mechanism extremely reduces the latency rate in SDRP compared to VELCT as show in Figure 1(b) in the SG. The proposed scheme based on its self-learning mechanism offers periodic scheduling of MSs as a function to observe the predictability of SNs, which generate information at higher frequencies in different regions in the SG. Hence, each mobile sink in SDRP collects more time-sensitive events data compared to VELCT in the SG. This has a great impact on SDRP network throughput compared to VELCT as shown in Figure 1(c). Moreover, in the case of an RSN failure, the SDN controller rapidly detects and reconfigures broken links in the SG. As a result, it significantly reduces the energy consumption of sensors by reducing network control message overheads and thus increases the NLT of SDRP as shown in Figure 1(d). One of the main issues in VELCT is that, the gathered information due to these issues cannot be delivered to the mobile sinks, which degrades overall network throughput performance in the SG. Moreover, the low speed than a predefined threshold value lead to sensor buffer overflows which results in dropping data success rate slightly drops in VELCT. The main reason of high-energy consumption in VELCT is due to increasing number of data forwarding SNs consume a notable amount of SNs energy in the network. Moreover, it also increases the probability of high latency because of path loops, corrupted data packets and uneven E_c in the SG. Finally, during finding new routes for data transmission also require a large number of communication overheads, which consume SNs energy and thus the NLT decreases rapidly in VELCT. In sum, compared to VELCT, the SDRP scheme is extremely suitable for observing smart grid events and thus provide power supply in an efficient, sustainable and economical manner with minimal impact on the environment in SCs.

IV. Summary And Future Work

One of major's area of concern in the smart cities is to provide continuous and quality-aware power supply to buildings, factories, transport sector, etc., to perform routine activities. In this context, the smart grid is a vital intelligent technology that can provide energy in a more efficient, efficient, sustainable and economical manner. In this context, this paper presented a novel opportunistic data gathering using the Internet of software-defined mobile sinks and WSNs in the smart grid. The extensive simulations performed through the EstiNet9.0 show that the proposed scheme is efficient for QoS-aware data collection compared to existing routing solutions in the SG. As a future work, the researchers are interested in designing a novel mobility mechanism to minimize control message overheads between rendezvous and normal sensor nodes in the SG.

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