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þÿKhalifeh, Ala

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Double Mobile Sinks Architecture for WSN Data Gathering and Critical Events Detection

Ala' F. Khalifeh[1] , Husam Abed[1] , Khalid A. Darabkh[2], Savvas Chatzichristofis[3], and Zinon Zinonos[3]
[1]Dept. of Electrical and Communication Engineering, German Jordanian University, Amman, 11180, Jordan
Email: (ala.khalifeh@gju.edu.jo, h.abed266@gmail.com)
[2]Dept. of Computer Engineering, The University of Jordan, Amman, 11942, Jordan, Email: k.darabkeh@ju.edu.jo
[3]Dept. of Computer Science, Neapolis University Pafos, 8042 Pafos, Cyprus
Email: {s.chatzichristofis, zinon.zinonos}@nup.ac.cy

Abstract*— Data gathering and critical events detection are two essential functionalities for Wireless Sensor Network (WSN). In this paper, we propose double mobile sinks network architecture, where two mobile sink nodes visit the Cluster Heads (CHs) to collect the captured data, which is very energy effective in terms of energy transmission efficiency and reliable compared with the case of having one static sink node. Moreover, the proposed architecture provides a capable scheme for supporting critical and non-critical data, which assures a timely delivery for any critical event to the remote monitoring and decision-making center with minimal interference to the non-critical data. Our proposed architecture shows a superior performance in terms of packets transmission delay, and requires low buffer occupancy for the CHs nodes when compared to related work in the literature. Finally, the paper provides a preliminary hardware design and implementation for the proposed architecture.

Keywords*— WSNs, Spiral trajectory, CHs, Mobile sensor node.

I. INTRODUCTION

With the advent of new emerging technologies such as the Internet of Things (IoT), cloud computing, big data, Wireless Sensor Network (WSN) is playing a vital role in facilitating these technologies and providing a scalable and reliable infrastructure. In WSN, a set of nodes equipped with several sensors are used to measure certain parameters about the Area of Interests (AoI). These values are sent to a remote monitoring and decision-making center that is responsible for analyzing the data and evaluating the AoI situation, thus assist in making the right decision and taking the needed actions. As depicted in Fig. 1, WSN consists of static nodes that are normally grouped into several clusters, where each cluster has a superior node called a Cluster Head (CH) [1]. The cluster nodes send the captured data to the CH, which in turns sends the data to a sink node. The sink node collects all the data and forward it to the remote center and monitoring station, where data are stored, processed and a decision is made concerning the AoI situation. Another important application of WSN is critical events' detection, where the sensor nodes are designed to detect certain critical events of interests (e.g. gas leakage, fire, nuclear pollution, etc.) and send it immediately to the remote center for an immediate response and action [2, 3]. In order to have an efficient WSN in terms of reliability and energy efficiency, several crucial parameters have to be optimized, among which is the sensor nodes' energy consumption, especially that these nodes are battery operated and are normally deployed in remote areas, which make their batteries difficult to recharge. In WSN, the transmission energy is the most prevalent energy consumption functionality that most of the researchers attempt to optimize [4]. Therefore, sensor nodes are deployed randomly in the AoI, and then grouped into several clusters, where one superior node acts as a CH. The CH is normally equipped with a greater capacity battery compared to the other nodes, thus enabling it to operate for longer period and with lower sleeping time. On each cluster, the cluster nodes send their captured data to the CH, which in turns will send them to the sink node. The sink node is designed to have high power capability and long range wireless communication interface, which enables it to send the aggregated data to the remote monitoring and processing center for further processing and decision making.

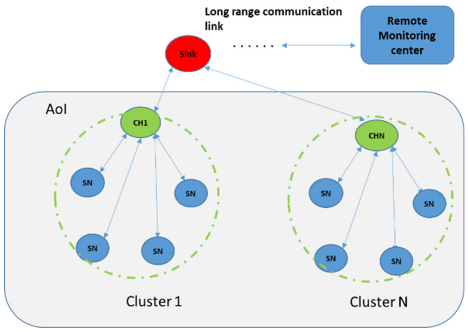

Fig. 1. Typical wireless sensor network with N clusters, one static sink node and a remote monitoring and processing center

In order to optimize the CH energy consumption, researchers proposed to utilize a mobile sink node that can navigate autonomously into the AoI until it reaches the CH nodes, where data is transmitted using very-minimal power due to the short transmission distance between the sink and CH nodes [5]. This solution saves significant transmission energy, due to the close proximity between the CH and the sink nodes; however, it has several challenges when it comes to the end-to-end delay and the CH buffer space, especially when having a time-sensitive critical event, which needs a fast transmission media and an immediate reaction from the remote monitoring center. The aim of this paper is to tackle these two challenges by proposing an efficient network architecture that utilizes two mobile sinks that traverse the AoI. The proposed mobility scheme ensures optimizing the CH energy transmission, while at the same time providing a reliable and fast wireless communication link to transmit critical events to the remote monitoring center. The rest of the paper of the paper is organized as follows: Section II summarizes the most related work in the literature. Section III describes the proposed double mobile sink WSN architecture. Section IV shows the performance evaluation of the proposed architecture. Finally, section V concludes the paper and proposes future work.

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II. RELATED WORKS

In order to reduce the data transmission energy consumption in WSNs, the integration of mobile nodes is performed. Sink mobility is one of the major methods in implementing nodes mobility in WSNs. Mobility for the sink mostly indicates that the system puts more burdens on the sink node instead of focusing on the sensor nodes, because the sink node is considered to have unconstrained power supply and much larger processing capability than the sensor nodes.

Luo et al. [5] proposed a routing protocol (MobiRoute) that utilizes a mobile sink to improve the network lifetime. MobiRoute optimizes the energy consumption of the sensor nodes by moving the sink node to achieve equilibrium to the traffic load among the nodes, thus enhancing the network lifetime. The proposed protocol showed its effectiveness for different network topologies and scenarios. In [6], the authors proposed a sink mobility approach to enhance the network lifetime. This is achieved by deciding where to position the sink throughout the network operation. The authors proposed a strategy designed for infrequent events, which is based on a heuristic geometric approach, where it is designed to react for a random event of unknown locations, starting time and duration. The main objective is to optimize the energy consumption and extend the network lifetime. The authors in [7] proposed a mobile sink WSN that aims at maximizing the network lifetime while tolerating delay. To achieve that, the sensor nodes do not send the data once it is available, instead, they wait until the mobile sink is located in an optimal location that minimizes its energy consumption.

Asad et al. [8] proposed an optimal clustering architecture that utilizes a Mobile Sink (MS) node to reduce the nodes' transmission energy. In this work, two routing protocols were proposed that are based in a spiral mobility trajectory. The first one is the Spiral Mobility based on Optimized Clustering (SMOC) used for data extraction for small WSNs, while the other is the multiple sinks based on SMOC (M-SMOC) used in large WSNs. In the first protocol, one MS is used to collect data from the sensor nodes, where the MS moves over a spiral trajectory toward the cluster nodes. The same idea is used for larger WSNs where four MS nodes are used to cover the AoI. The reason for increasing the number of MS is to reduce the delay, which is very crucial especially in larger WSNs. Since the MS node location is changing over time, sensor nodes belonging to the various clusters who detected a critical event are allowed to send directly to the moving sink node, if the distance between the node ($D_{i,s}$) and the mobile sink is less than the distance between the node and the CH ($D_{i,ch}$). If the nodes have non-critical data, they should wait for their TDMA slot, and send it to the CH node. However, as will be depicted in the proposed network architecture, the single mobile sink assumption has several drawbacks such as it requires the CHs to have high storage buffer space, to save the received packets from the sensor nodes until the mobile sink arrives to gather the CH packets. Further, the way the authors addressed the dissemination of the nodes with critical-data event is not efficient in terms of the end-to-end delay, and reliability.

From the conducted literature review, it is notable that most of literature work focuses on how to conserve nodes' energy based on CHs and sink node deployment without optimizing the transmission delay, especially for critical data events. The aim of this paper is to propose a network architecture that achieves optimal energy consumption, reducing the storage buffer space needed by the sensor nodes, and providing a fast and reliable communication link for the critical event data.

The proposed work complements our prior work that aimed at designing and implementing an efficient and practical WSN [2, 3], that prolongs the WSN lifetime by optimizing the clustering [1, 9, 10], routing [11] and minimizing the interference [12].

III. THE DOUBLE MOBILE SINKS WSN ARCHITECTURE

The proposed network is established by performing three main phases: Nodes' deployment and clustering, Mobile sink nodes initialization, and sink nodes navigation.

A. Phase 1: Nodes' deployment and clustering

As depicted in Fig. 2, the proposed network consists of a set of static Sensor Nodes (SNs) deployed randomly over the AoI. The optimal number of CH needed (K_{opt}) is estimated using Eq. (1) [13], where n is the number of SNs.

$$K_{opt} = \sqrt{\frac{n}{2\pi}}\left(\frac{2}{0.765}\right) \tag{1}$$

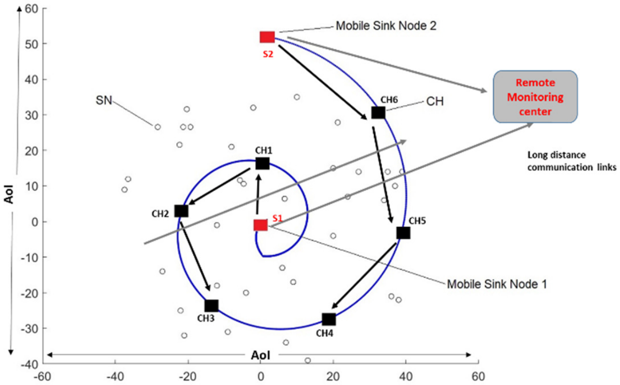


Fig. 2 The double mobile sinks WSN architecture

Once the optimal number of CH nodes is determined, the CH nodes are deployed over the AoI using the spiral trajectory, which proved to achieve optimal coverage for the AoI, while balancing the energy consumption among the nodes, thus extending the network lifetime [14, 15]. A proposed algorithm developed with nodes' pre-deployment using UAV or airplane that moves on a spiral trajectory to land the CHs as presented in [7]. To deploy less CHs to achieve full coverage, a node placement policy is used, which can be summarized as follows. If the distance between any two CHs is equal to $\sqrt{3}\,Rs$, then there should be no hole and only minimal overlap in the area. The node placement policy is stated such that the airplane deploys a sensor node for every distance of $\sqrt{3}\,Rs$, where Rs is the CH coverage radius.

Once the CHs are deployed over the spiral trajectory, the SNs are clustered such that nodes will be associated to the nearest CH, which can be detected by comparing the Relative Received Signal Strength Indicator (RSSI) of the CHs' beacon signals [16]. At this phase, the clusters are performed and the network is ready to start sending the AoI and transmitting the sensed data to the sink node, which in turns can send it to the remote monitoring center.

B. Phase 2: Mobile sink nodes initialization

In order to optimize the CHs' transmission energy consumption, the sink node is assumed a mobile node, and in the proposed network architecture, two sink nodes are proposed. A shown in Fig. 2, the first one is located in the center of the spiral trajectory, which will start traversing the network by moving to CH1, which is identified as the starting point for the first sink node ($S_{1,\ CH1}$). Similarly, the second sink node will move to the CH located in the spiral outer region (i.e. CH6), which will also be identified as Sink 2 starting point, which happened to be CH6 in this network architecture ($S_{2,\ CH6}$).

C. Phase 3: Mobile sink nodes navigation

Once the sink nodes are located in their initial locations, the nodes will start sending the sensed data to the CH using Time Division Multiple Access (TDMA), and the sink nodes will start moving toward the CH nodes to receive the captured data. Notice that at the starting time (t_0), CH1 and CH6 will not have yet any data to transmit to S_1, and S_2, respectively, thus the sink nodes will move to the next CHs (S_1 will move to CH2, while S_2 will move to CH6). Both sinks know the locations for the CHs assigned to them. Define S_{1CHs}, S_{2CHs} as the CHs assigned to S_1, S_2, respectively. According to Fig. 2, S_{1CHs} :{ CH1, CH2, CH3}, S_{2CHs}:{CH6, CH5, CH4}. Knowing the locations of the CHs, the sink nodes can estimate and adapt the moving speed needed to arrive to the next CH within a predetermined time interval (T), such that both sinks will reach the CHs at the same time. This assumption allows equal data gathering times for all the cluster nodes. While the sink nodes are moving toward the CHs, the CHs are continuously gathering packets from their corresponding cluster sensor nodes. The amount of packets collected during T, denoted as P, is estimated using Equation (2).

$$P = T\,BW/P_s \ , \tag{2}$$

where BW is the wireless link bandwidth used to transfer packets from the sensor nodes to the cluster head, P_S is the packet size in bits. Notice that T should be chosen according to Equation (3).

$$T \ \geq\ m\,N_c\,D_p \ , \tag{3}$$

where N_c is the size of the smallest cluster established in the network, m is an integer number that is chosen according to the application delay requirements, since the larger m , the larger number of collected packets during T, and the longer delay it takes to send them to the sink and remote station. D_p is the packet transmission delay calculated using Equation (4).

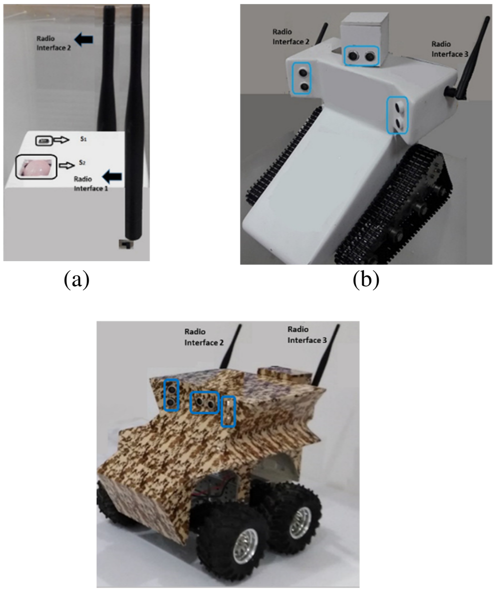
$$D_p = P_s/BW \tag{4}$$

D. System implementation

A preliminary hardware prototype for the suggested WSN has been built. Fig. 3 (a) depicts the SN and CH nodes design, where the nodes are equipped with two radio interfaces. The first one is used to collect non-critical data using a predetermined radio frequency channel (R_1), while the second radio interface (R_2) is used to transmit critical data, which could happen at any time while the nodes are transmitting the non-critical data using their allocated TDMA time slot. Therefore, in order to allow simultaneous transmission of both data streams (the critical and non-critical), the second radio should utilize different frequency channel (R_2) that does not overlap and interfere with R_1. In the proposed implementation, the ZigBee IEEE 802.15.4 wireless technology is utilized where R_1 utilized the 2.4 GHz spectrum, while R_2 utilized the 900 MHz spectrum. Both wireless transceivers, with two sensors (s_1, s_2) are attached to microcontrollers powered by a battery. In this implementation, the Waspmote microcontroller developed by Libelium Inc. [17] is used, s_1 is a sensor used to measure the temperature, humidity, pressure, and s_2 is a motion detection sensor. The mobile sensor node is depicted on Figs. 3 (b, c), which show Unmanned Ground Vehicles (UGVs), that can move according to predefined GPS locations, while avoiding obstacles using a set of ultrasonic sensors (marked in blue color). Two radios are attached to this UGV, where the first module is similar to the R_2 available at the CH node, which can be used to transfer the captured data from CH to the sink node. It can also be used to receive the critical data, while the other module (R_3) utilizes long range communication technology (e.g. LoraWAN [18]) to transfer the captured data (both the critical and non-critical) to the remote and monitoring center. This interface should use different frequency spectrum in order not to interfere with R_2. Notice that the remote monitoring center is normally located far from the AoI. Therefore, this radio interface (R_3) acts as the main gateway for the data captured by the CH nodes.

E. Critical events' detection

Notice that in the proposed network architecture, if the node detected a critical event (e.g. detect a sudden high rise in the temperature due to a fire critical event), then the node can send the critical alert immediately using its R_2 radio without interfering with the non-critical data transmission process, which occurs on R_1. The CH will receive this critical data utilizing its R_2 radio interface and send it directly to its sink node. Notice that in the proposed hardware architecture, the ZigBee DigiMesh [16] media access protocol is used, which in turns will send the critical data to either to the next hop CH node until it reaches the sink node in a multi-hop paradigm or directly to the sink node if the later was within the CH coverage area. Once the sink node receives this critical data, it will forward it immediately to the remote monitoring center utilizing its long-range wireless module (R_3). It is also important to mention that this immediate reaction and response was possible due to the availability of two radio modules on the sensor nodes. However, if installing these radios were expensive, especially that sensor nodes are normally large in number, as they need to cover large AoI, then the sensor nodes can utilize one radio module (R_2 for example) , and the node with the critical data has to wait until its allocated TDMA slot, which may cause some delay. However, the CH node still needs to have two wireless radio modules to allow simultaneous data transmission to the sink node using its R_2 interface, while it is keep receiving the sensor data using its R_1 interface.



(a) (b)

(c)

Fig. 3 The hardware implementation of the (a) SN and CH nodes,(b) tractor and, (c) wheeled mobile sink nodes

IV. PERFORMANCE ANALYSIS

To evaluate the effectiveness of the proposed network architecture, a comparison between the proposed architecture and the one proposed in [8] depicted on Fig. 4 is conducted. In order to show the effectiveness of the proposed architecture, the data packet gathering process, and the CH nodes buffer occupancies are shown in Fig. 5 for both the single sink and the proposed double sinks architecture.

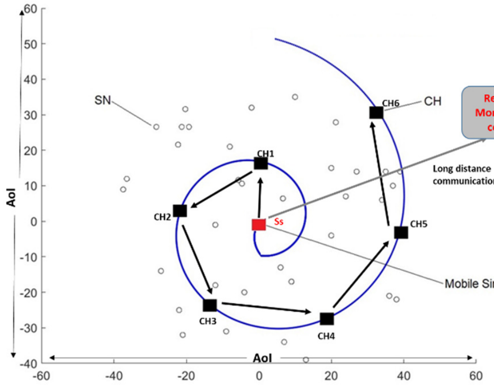
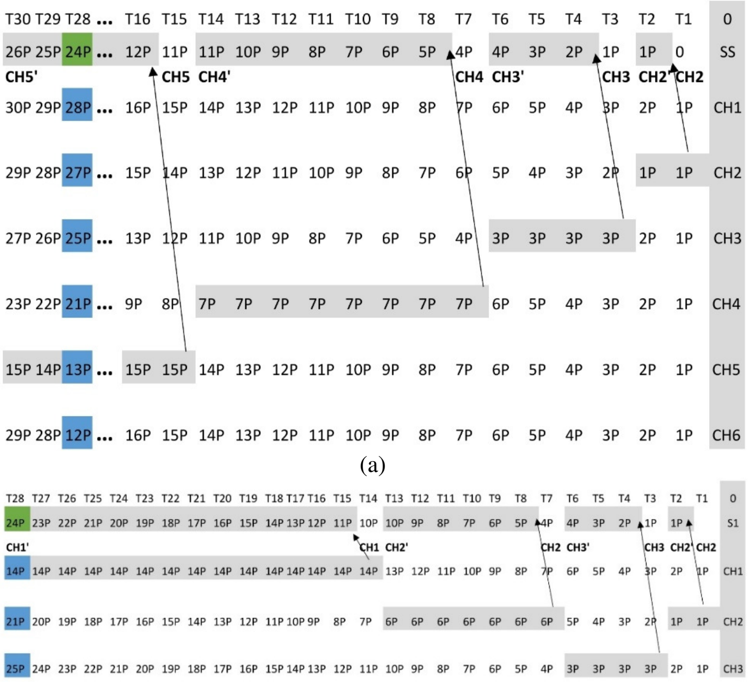


Fig. 4 Single sink spiral mobility clustering WSN architecture [8]

The main parameters used in the simulation using Matlab are listed in Table 1. In fact, both architectures have almost the same transmission energy consumptions. However, as mentioned earlier, the main advantage of the proposed framework is apparent on the delay efficiency, interference mitigation, critical–data responsiveness, and finally, in the CHs buffer sizes occupancies, which will be illustrated in the below analysis. Figs. 5 (a, b) show the buffers occupancy matrix for both the CHs and the sink node(s), which is illustrated by the following scenario. Assume a set of sensor nodes (35 in this case), are deployed in $100 \times 100\ m^2$ AoI. According to Equation (1), the optimal number of CHs equals to 6, these nodes (CH1, CH2, CH3, CH4, CH5, CH6) are deployed over the AoI using a spiral trajectory described later. The CH coverage radius is $Rs = 18\ m$, which was concluded from our practical experience with ZigBee wireless technology. Accordingly, the locations of the CHs will be as follows: CH1(-.4, 17), CH2 (-22,2), CH3 (-13.5 , -23.5), CH4 (18.7, -27.4), CH5 (38.9, -2.8), and CH6 (32.6, 31.5), as shown in Figs. 2 and 4. In the initialization phase, for the double sink nodes network architecture depicted on Fig. 2, the first sink node (S_1) will move towards CH1, while the second sink node (S_2) will move towards CH6. Further, the CHs assigned to S_1, S_2 are S_{1CHs} :{ CH1, CH2, CH3}, S_{2CHs} :{ CH6, CH5, CH4}, respectively. However, for the single sink network architecture, the sink node (S_S) will move to CH1 and S_{SCHs} : {CH1, CH2, CH3, CH4, CH5, CH6}. To illustrate Fig. 5, let us focus first on the single sink case, i.e. Fig. 5 (a). In the initialization phase, S_s will move to CH1 as the starting point. At that time, the sensor nodes will start sending packets to CH1, and this is considered the starting time of the data gathering process (t_0), S_S will leave CH1 since it still needs time to capture packets. Therefore, S_S moves directly towards its next CH as mentioned in its S_{SCHs} list, i.e. CH2. Upon its arrival time ($T_2 = t_0+T$) and during the trip time (T), the cluster nodes will send packets to the CHs. Therefore, when Ss reaches CH2, the number of packets accumulated in CH2 is equal to P, the sink node starts collecting the packets from CH2 utilizing its radio interface R_2, while at the same time, the cluster nodes continue to send their packets to CH2 using R_1. At the end of $T2$, the number of packets collected by the sink node is equal to P, and the number of packets accumulated in the clusters CH3-CH6 is equal to $2P$ each. It is important to mention that the amount of gathered packets on CH1 is equal to P, since only $1T$ elapsed since S_S left the node. Finally, it is also important to mention that once S_S leaves CH2, the amount of accumulated packets that will be stored in CH2 until S_S visits it again is P. This is because while S_S was receiving the accumulated packets in CH2 (P) using the first radio interface (R_2), CH2 was also receiving packets from the senor nodes using the other radio interface (R_1). After that, S_S will move towards the following CH, in our case, it is CH3. At the arrival time ($T3$), which is marked in the figure as **CH3**, the amount of collected packets at CH3 is equal to $3P$, therefore, S_S will stay at CH3 for a duration equals to $3T$ to be able to collect the captured packets, and will leave CH3 at time $T6$, which is marked in the figure as **CH3'**. Notice that the amount of accumulated packets by S_S after leaving CH3 is equal to $4P$, whereas CH3 has already accumulated $3P$ at this time, since it was receiving packets from its sensor nodes during the elapsed period ($3T$). Notice that these packets will be stored until the next visit for S_S, and the amount of accumulated packets on the other CHs are significantly increasing ($6P$) on each CH4, CH5, and CH6. The process continues until S_S visits all the

CHs on the spiral trajectory. After that, S_S will traverse the CHs in the reverse order (i.e. CH6, ... , CH1). Fig. 5 shows the accumulated packets until S_S leaves CH5. Now, we compare that with the double sinks case, depicted on Fig. 5 (b), which is shown only for the first sink node (S_1). It is notable that S_1 was able to reach CH2, CH3, then go back to CH2, and finally reaching CH1 and leaving it on a total duration of 28T, while it took S_S 28T just to reach and leave CH5. Further, Fig. 6 compares the amount of received packets (in terms of P), and the accumulated delay for the received packets at the sink node (in terms of T), for the double and single sinks, which shows a superior performance of around 50% of the proposed architecture.



T30	T29	T28	…	T16	T15	T14	T13	T12	T11	T10	T9	T8	T7	T6	T5	T4	T3	T2	T1	0
26P	25P	24P	…	12P	11P	11P	10P	9P	8P	7P	6P	5P	4P	4P	3P	2P	1P	1P	0	SS
CH5'					CH5	CH4'							CH4	CH3'			CH3	CH2'	CH2	
30P	29P	28P	…	16P	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	2P	1P	CH1
29P	28P	27P	…	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	2P	1P	1P	CH2
27P	26P	25P	…	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	3P	3P	3P	2P	1P	CH3
23P	22P	21P	…	9P	8P	7P	7P	7P	7P	7P	7P	7P	7P	6P	5P	4P	3P	2P	1P	CH4
15P	14P	13P	…	15P	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	2P	1P	CH5
29P	28P	12P	…	16P	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	2P	1P	CH6

(a)

T28	T27	T26	T25	T24	T23	T22	T21	T20	T19	T18	T17	T16	T15	T14	T13	T12	T11	T10	T9	T8	T7	T6	T5	T4	T3	T2	T1	0
24P	23P	22P	21P	20P	19P	18P	17P	16P	15P	14P	13P	12P	11P	10P	10P	9P	8P	7P	6P	5P	4P	4P	3P	2P	1P	1P		S1
CH1'														CH1	CH2'						CH2	CH3'			CH3	CH2'	CH2	
14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	2P	1P	CH1
21P	20P	19P	18P	17P	16P	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	6P	6P	6P	6P	6P	6P	5P	4P	3P	2P	1P	1P	CH2
25P	24P	23P	22P	21P	20P	19P	18P	17P	16P	15P	14P	13P	12P	11P	10P	9P	8P	7P	6P	5P	4P	3P	3P	3P	3P	2P	1P	CH3

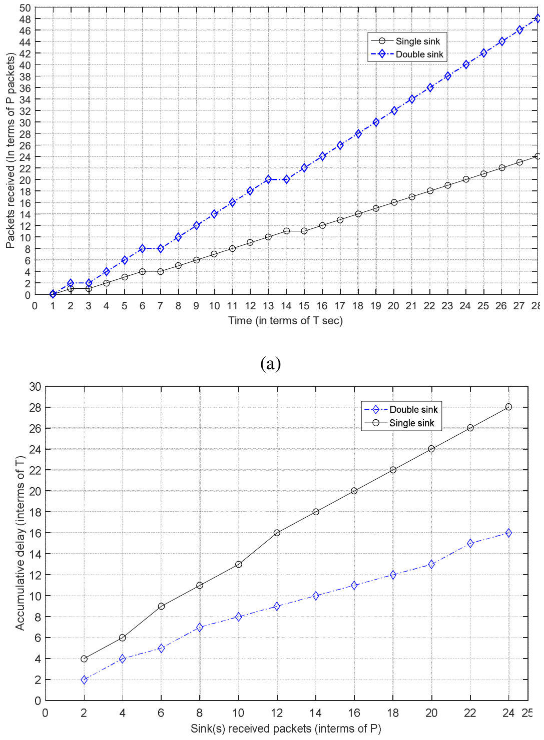
(b)

Fig. 5 The amount of collected packets as a function of T by the sink node and by the CHs nodes for the (a) single (b) double sink nodes, where the buffer occupancies for the first sink and its associated CHs are shown.

Moreover, it is important to mention that the amount of buffer space needed at the CHs to keep the accumulated packets until the mobile sink nodes visit them is much higher in case of the single sink node, when compared with the double sink nodes. The buffer space requirements for the CH nodes will be exacerbated when large number of sensor and CHs are deployed to achieve higher sensing and coverage capabilities for the AoI. Finally, as described in Section III, the proposed architecture is well suited to respond promptly to critical events, this is due to the well-designed hardware architecture, which ensures that both critical and non-critical data are sent seemingly and smoothly with minimal interference. However, the way of handling the critical data delivery aspects were not well described and handled in the single sink network architecture proposed in [8]. The authors mentioned that critical data could be sent directly to the sink node, only if the distance between the sensor node and the sink node is closer than the distance between the node and the CH. However, if the distance is larger, then the node will send it directly to its CH, which may take significant time until the sink arrive to the CH and collect this critical data.

Table 1 Matlab simulation parameters

Description	Value
Number of nodes	35
AoI	$100\,x100\ \mathrm{m}^2$
Transmitter electronics (ETX-elec) Receiver electronics (ERX-elec) (ETX-elec) = (ERX-elec) = (Eelec)	50 nJ/bit
Energy consumed by the amplifier to transmit at a shorter distance ϵfs	100 pJ/bit/m^2
Energy consumed by amplifier to transmit at a longer distance ε_{amp}	0.0013 pJ/bit/m^4
Initial power	0. 5 J
Packet size	2048 bit
Number of optimal clusters	$kopt = \sqrt{\frac{35}{2\pi}\cdot\frac{2}{0.765}} = 6$



(a)

(b)

Fig. 6 A comparison between the single and double sinks network architecture showing the amount of (a) received packets, and (b) the accumulated delay needed to receive them at the sink node.

V. CONCLUSION AND FUTURE WORK

In this paper, an efficient network architecture that is based on utilizing double mobile sinks node navigating on the AoI is proposed. The sink nodes move to the CHs, which are deployed on a spiral trajectory, and collect the data thus reducing the transmission energy and improving the network lifetime. The proposed architecture has better delay for both critical and non-critical data, when compared with the single mobile sink architecture. Further, it does not require CHs to have high buffer space due to its short round trip, when compared with the single sink case. A preliminary hardware design and implementation is described. As a future work, we are still working on testing the proposed hardware components, integrating them together and conducting an experimental evaluation of the proposed architecture

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