A Simulation Study for UAV- Aided Wireless Sensor Network Utilizing ZigBee Protocol

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***Abstract*— Wireless sensor networks have been used in several applications to perform remote monitoring for a certain Area of Interest. In this work, we propose to utilize an Unmanned Aerial Vehicle (UAV) to improve the ground network connectivity, act as a data mule that collects the captured data and off-load the ground sensor nodes, who have normally limited storage capacities. We have investigated the effect of several parameters that affect the communication between the UAV and the ground sensors such as the UAV height, communication channel weather conditions, and nodes' noise factor, and evaluated the network performance measured by the average packet loss rate, end-to-end delay, and throughput. We found out that when the nodes' transceivers have a relatively high noise factor (above 20), it is recommended to keep the UAV altitude around 150 meters or below. We also noticed that the performance degrades drastically when having severe weather conditions, which requires additional mechanisms for improving the transmission performance such as the usage of error correction codes and Multiple Input Multiple Output antennas.**

Keywords- Wireless sensor networks, UAV, 802.15.4, ZigBee

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have been proposed to be used for various applications and scenarios, remote sensing and monitoring is one of these scenarios in which sensor nodes equipped with specific sensors, are used to measure application specific parameters in an Area of Interests (AoI). For instance, WSNs can be used to improve the irrigation process by measuring some relevant parameters such as the environment temperature, air pressure and speed, soil humidity, etc., and sending the captured data either fully or partially to a central location for further analysis and decision-making. To achieve that, the sensor nodes are distributed in the AoI to form a cluster, where a Cluster Head (CH) is selected which will receive all the captured data from the other cluster member nodes. The CH will send the data to a remote area for further analysis and decision-making using a long-range wireless technology such as mobile-based communication protocols like 3G (HSPA), 4G (LTE), and point-to-point Radio Frequency (RF) communication. Unmanned Aerial Vehicles (UAVs) have been recently attained the researchers' attention for their myriad benefits and potential usages for several applications and scenarios. Furthermore, the UAV technology is also motivated by the NATO report for their potential usages in the future [1]. In the literature, some researchers have proposed to integrate a UAV to the ground sensor network in order to assist in the routing process by providing an alternative route, which may have less interference than the other ground routes [2, 3]. The authors in [4] proposed a platform that utilizes both sink and source nodes mobility and integrates WSNs with UAVs and actuators, while addressing the challenges associated with sensors' mobility. Further, the authors in [5] discussed the potential of using a UAV to spray crops with the capability of self-adjusting its route in case of having climatic conditions during the spraying process, based on the received feedback from the ground sensor nodes, which in turns improves the spraying efficiency. Some researchers described the WSN aided by a UAV or another node above the other ground nodes as a three-dimensional wireless sensor network, where they focused on studying the network connectivity and coverage [6, 7]. Our literature review showed that most of the work did not consider the effect of the UAV altitude, weather conditions, and nodes noise factor on the transmission performance, which is very crucial and essential to the network operation.

This paper continues our ongoing research work [8-11] that aims at providing a Hybrid Wireless Sensor Network (HWSN) that utilizes ground sensors and UAVs to remotely monitor an IoA. This target has been achieved by providing energy efficient clustering algorithms [8], traffic aware medium access control mechanisms [9], interference mitigation modulation, clustering and medium access control schemes [10,11]. In this work, we propose to utilize an UAV for increasing network connectivity by acting as a data mule that drives the information collected by the static sensors towards a possibly remote collection and processing center, which will not require a long distance data transmission over the open wireless channel, thus increasing the system security. This paper studies the transmission performance between the ground sink node and the UAV, taking into account several factors such as the UAV height, weather conditions, and noise level at the sensors and UAV nodes, which were not well addressed by the literature, as most of the literature work discussed the idea of utilizing a UAV integrated with the static sensor network, but without focusing on the transmission performance between the aerial and the ground nodes. The rest of the paper is organized as follows: Section II discusses briefly the utilized ZigBee protocol and the network architecture. Section III demonstrates the simulation results. Section IV concludes the paper and proposes future work.

II. ZIGBEE PROTOCOL AND NETWORK ARCHITERCTURE

In this section, a brief description about the ZigBee wireless protocol, and the network architecture utilized in this work is provided.

A. ZigBee Protocol

The IEEE 802.15.4 protocol defines the Medium Access Control (MAC) sub-layer and physical layer for Low-Rate Wireless Private Area Networks (LR-WPAN). The IEEE 802.15.4 protocol is typically connected with the ZigBee protocol. The ZigBee specification determines the protocol layers above IEEE 802.15.4 [12].

B. IEEE 802.15.4 Network Devices and Topology

The IEEE 802.15.4 standard divides the network devices into two generic types: Full Function Device (FFD) and Reduced Function Device (RFD) [12]. FFD is a device that provides all IEEE 802.15.4 MAC services. It supports three operation modes: a Personal Area Network (PAN) coordinator, which is the main controller of the network. Its roles are as follows: Assign a PAN ID to the networks, select radio frequency for the network operation, and assign an address to itself. The second operation mode supported by IEEE 802.15.4 is the coordinator, which provides synchronization services through the transmission of beacon signals. Such a coordinator must be associated to a PAN coordinator and does not create its own network. The third operation mode is simple device, which is a device that has input/output function but no coordinating functionalities. A LR-WPAN must include at least one PAN coordinator. The network topologies that can be used with IEEE 802.15.4 are star, tree, and mesh [12]. In this work, the star network topology is utilized.

C. IEEE 802.15.4 Medium Access Control

The MAC sub-layer of the IEEE 802.15.4 protocol and the MAC sub-layer of the IEEE 802.11 protocol share many features, using of CSMA/CA as a channel access protocol is one example, the support of contention-based and contention-free periods is another example. The PAN coordinator can select one of the following operational modes supported by the MAC protocol [12]:

1) Beacon-enabled mode: in this mode, the PAN coordinator periodically generates beacons called Beacon frames, to synchronize the attached devices and to identify the PAN. The nodes can work under contention free periods utilizing a pre-defined time slots named as Guaranteed Time Slots (GTSs), or under a contention period utilizing slotted CSMA/CA.
2) Non Beacon-enabled mode: in this mode, the PAN coordinator does not assign any time slots to the attached devices. The devices can simply send their data by using slotted CSMA/CA.

D. Network Architecture

Figure 1 depicts the network architecture utilized in this work, which consists of a set of static ground nodes. Each node has a set of sensors that captures certain measurement of interest (e.g. the temperature, pressure, humidity, etc.) for the AoI, and a wireless transceiver that sends the captured data frequently to the sink node. The UAV node will communicate with the sink node and transfer the collected data to a remote monitoring center for further analysis and decision making. Notice that this mechanism guarantees a more stringent security measure, as oppose to send it wirelessly over long distance, which exposes the wireless signal for potential intruders and eavesdroppers.

In the following section, a performance analysis for the proposed network architecture is provided, taking into consideration the UAV height as well as the weather condition of the communication channel and the noise level at the nodes' transceivers.

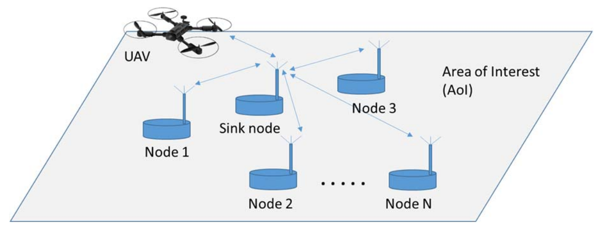

Figure 1 Wireless sensor network aided by a UAV

III. SIMULATION RESULTS AND DISCUSSION

The aim of this section is to study the performance of the proposed network architecture taking into account several aspects such as: the UAV height, channel weather condition, and nodes transceivers' noise level.

A. UAV Height and Nodes Transcievers' Noise Level

The proposed network is simulated using the Qualnet simulator [13]. The network consists of 12 ground nodes (four coordinators, seven FFDs, and one PAN coordinator which acts as the sink node). All the nodes send data to the sink node, which in turns forwards it to the UAV node. The sink node has to be configured to have enough buffer size to store the data received from the other nodes, waiting for the UAV to arrive to an exact point where it starts transmitting the buffered packets. The UAV collects the data from the sink node where the sink node buffers the packets using First in First out (FIFO) queuing scheme, then it moves around the sink node for enough time duration to collect all the data from the sink node. The UAV node is assumed in this simulation to be always in the range of the sink node, and data is going to be forwarded directly from the sink node to the UAV.

Each node transmits 1000 packets of 70 bytes each; they start the transmission after the second minute of the simulation time. All nodes in the network transmit packets at 3 dBm transmission power using IEEE 802.15.4 MAC protocol. The PAN coordinator provides GTSs to the nodes to transmit packets at a specific time slot in order to avoid packet loss in the network. Nodes are randomly distributed in an area of 1 square kilometer, which is covered by all the nodes in the network. The simulation time is set to be 60 minutes. A certain path is set to the UAV around the area of interest, which lasts to the end of the simulation of 60 minutes where the UAV receives all the packets from the sink node.

In this simulation, we used three different heights to the UAV to receive data, where they operate on different noise factors of the network. These heights are selected such that the UAV node remains connected with the sink node, taking into account the ranges that the ZigBee protocol can provide. This setup leads us to study the network performance in terms of packet loss, delay and throughput. In the first scenario, the network is configured with noise factor of values equal to 10, 20 and 30, which affects the network delay at three different heights of 100, 150 and 200 meters as shown in Figure 2. The noise factor reflects the thermal noise level at the nodes transceiver circuits, and it can be derived by taking the SNR at the input and dividing it by the SNR at the output of the transceivers' circuits.

It can be noticed that noise and height are affecting the average end-to-end delay of the network, it is clear to see that the noise factor is acceptable under the value of 20 but it becomes very high when it reaches the value of 30. However, the height of the UAV does not change the value of the delay in the noise factor values of 10 and 20, while it actually shows more effect on the value of 30. Figure 3 shows the effect of noise factor and height on the packet loss rate.

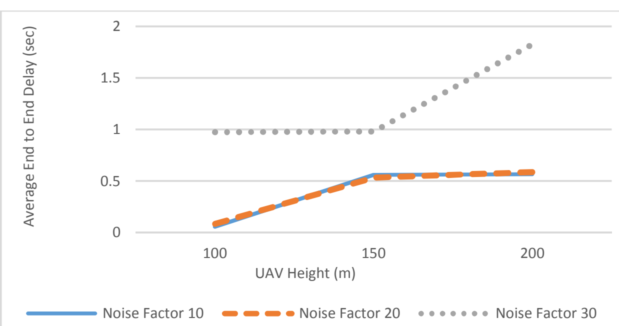

Figure 2 Average end-to-end delay (sec)

In this network, nodes transmit packets to the sink node according to their GTSs provided by the coordinator, which means the network would not face any kind of packet loss caused by network contention except during the GTSs assignment process. Average packet loss rate can reach almost zero at low heights since the noise factor is very low. However, the average packet loss rate increased to reach almost 50% at the height of 200 meters and noise value of 30, which means the UAV has to remain in the safety height of 150 meters or below and noise factor value of 20 to avoid excessive packet loss and performance degradation.

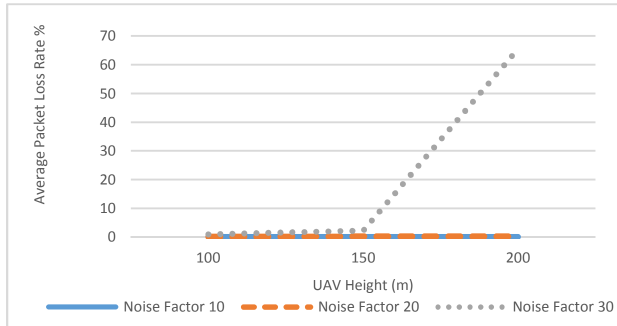

Figure 3 Average packet loss rate for different heights

Nodes' throughput has to be as high as possible which can be seen in Figure 4, where it degrades drastically when the heights and noise factor are above 150 meters, 20, respectively.

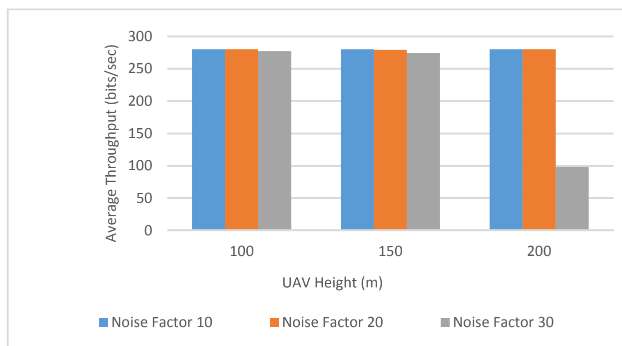

Figure 4 Average throughput (bits/sec) as a function of the UAV heights and noise levels

It can be concluded from the above figures that the effect of height increases when the value of noise factor increases, which means that both factors have to be taken into consideration when configuring the network parameters.

B. *Weather Conditions*

There are multiple aspects that affect the performance of the network which should be adjusted and considered in order to achieve the optimal results. One of these issues is being aware of the weather conditions and understand how it may affect the transmission quality. This paper assumes that the network nodes are deployed on an open space area, which means that weather has an obvious effect on wireless transmission process. In what follows, the effect of changes in weather intensity measured in precipitation in millimeters per hour [13], and the resulting effect on the network performance are studied. To achieve that, the UAV flies on an approximate height of 50 meters under different weather conditions. Figures 5, 6, and 7 show the average packet loss, end-to-end delay, and throughput, respectively as a function of the weather intensity.

As expected, it can be concluded from the figures that the weather affects the behavior of network on the average packet loss rate, end-to-end delay and throughput especially at high intensity levels. Thus, the network performance will degrade drastically at these levels, which mandates to use other techniques to improve the transmission quality such as using joint source and channel coding utilizing Forward Error Correction (FEC) codes, and using Multiple Input Multiple Output antennas [14], which should improve the transmission quality and reduce the bit error rate. Furthermore, it is important to mention that changing the UAV height with different weather conditions did not have any significant effect. As such, choosing the proper UAV height will be determined using other factors such as the noise factor and ground nodes' reachability.

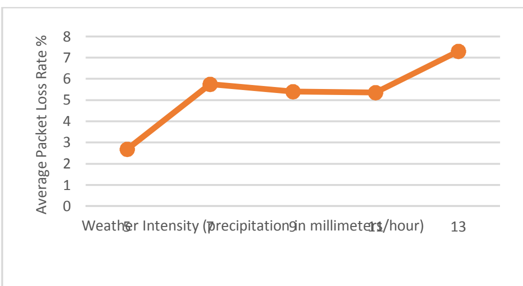

Figure 5 Average packet loss rate as a function of the weather intensity

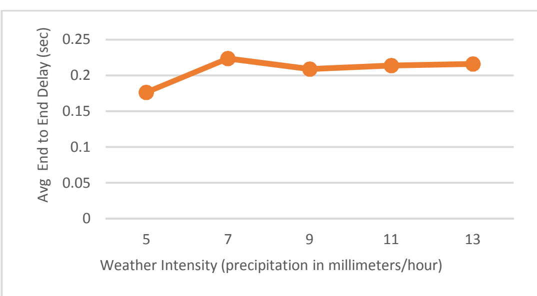

Figure 6 Average end-to-end delay (sec) as a function of the weather intensity

IV. CONCLUSION AND FUTURE WORK

In this paper, we presented a wireless sensor network that utilized an Unmanned Aerial Vehicle to act as a data mule, for the captured data collected by the ground sensor nodes. Several parameters that affect the transmission quality such as the UAV height, weather intensity measured in the precipitation in millimeters/hour, and nodes' noise factor have been investigated by measuring the packet loss rate, throughput, and end-to-end delay. As a future work, we are implementing the system experimentally in order to study these factors practically and exploring the potential of utilizing FEC codes and MIMO antennas to improve the transmission performance.

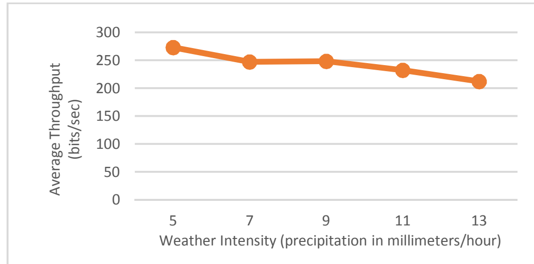

Figure 7 Average throughput (bits/sec) as a function of the weather intensity

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