Characterization of the Link Quality of a Coordinated Wireless Environment

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ABSTRACT

The joint use of Unmanned Aerial Vehicles (UAVs) and wireless sensor networks (WSN) enables to monitor dangerous and inaccessible places. However, the success of this deployment depends on the quality of the wireless links connecting the sensor nodes on the ground with one another and with the UAVs. These links are affected by several factors including the physical environment, the ease with which the UAVs navigate or hover, the energy reserve, wind, and the MAC protocols arbitrating the wireless media between the UAVs and the WSN. In this paper we present experimental results pertaining to link quality fluctuations, packet delivery ratio, channel symmetry, and continuous packet transmission success and failure statistics. Furthermore, we propose a probabilistic model for estimating the time a UAV requires to successfully collect k number of packets from a ground gateway.

CCS CONCEPTS

• **Computer systems organization → Sensor networks**; • **Networks → Network protocol design**; **Network measurement**; *Network dynamics.*

KEYWORDS

Wireless sensor networks, UAV, link quality fluctuation, Internet of Things, Cyber Physical Systems

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1 INTRODUCTION

There are several circumstances which endanger human presence but require close inspection and monitoring. The 2019-2020 coronavirus pandemic [7, 31] has demonstrated the vulnerability of human existence. A potential leak of toxic gases in a chemical industry, explosions, or earth quakes likewise pose significant danger to human presence [6, 20, 21]. During oil refinery, for example, toxic gases such as ammonia (NH_3) and hydrogen sulphide (H_2S) are produced as by-products and transported in pipelines. Ammonia is a highly reactive alkaline gas which is useful for producing refrigerants, fertilizers, and water and waste water facilities [18]. Likewise, hydrogen sulphide is useful for manufacturing sulphuric acid, cosmetics, and rubber products [19]. But these gases are toxic and flammable [27] and a leak in the transporting pipelines can endanger human life as well as the environment [3].

In such circumstances the coordination of wireless sensor networks and unmanned aerial vehicles (UAV) such as drones can be very useful for remotely detecting, monitoring, and even fixing leaks [10, 25]. Similar applications such as determining the extent of damage after the collapse of complex buildings or bridges following an earthquake or a man-made disaster can be thought of [30]. However, the success of such a deployment depends on the reliability of the wireless links required to establish node-to-node and node-to-UAV communications and the response time of the whole system. These aspects, in turn, depend on many factors including the physical environment, the placement of the nodes, the drive quality of the UAVs, and wind, among others.

From a technical point of view, several decisions have to be made (1) to determine the organisation of the wireless sensor network (WSN) to efficiently collect data, (2) to interface the network with a UAV or UAVs, and, if multiple UAVs are used, (3) to coordinate between the UAVs. Typically, a WSN consists of several wireless sensor nodes one of which is designated as a base station. The predominant network traffic flows towards this base station. With the use of a UAV or multiple UAVs, designating a single node as a base station is neither practical nor optimal. Nor is it optimal to let individual nodes interact with the UAVs directly. Which nodes should interact with the UAVs directly depends on several factors such as the size of the area being monitored, the difficulty associated with navigating the UAVs, and the response time of the system.

As far as the WSN is concerned, it is reasonable to designate as gateways those nodes which are highly connected with their neighbours. If we consider Fig. 1, for instance, nodes A, B, and C appear to be good candidates owing to their high node degrees. Designating many nodes as gateways is not necessarily an advantage, however, as this requires complex coordination both within the WSN and between the WSN and the UAVs. Furthermore, the densely connected nodes may not necessarily be spatially well distributed, in which case different leaf nodes may experience different end-to-end latency which may affect the quality of the data analysis. Suppose one decides to have two gateways in Fig. 1. Which of the nodes are most suitable and why? We may answer these questions by aiming

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to minimise the average end-to-end latency of packet transmission. In this regard, by looking into the topology, it appears reasonable to designate Nodes A and C as gateways. If, on the other hand, we wish to have just a single gateway, the node which is placed centrally appears to be the most suitable candidate, which is node B.

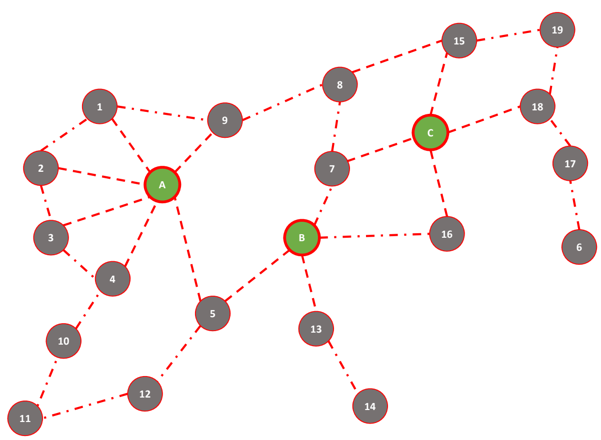


Figure 1: The deployment scenario of a wireless sensor network for toxic gas detection.

As far as the quality of the wireless link is concerned which the ground network establishes with the UAVs, many factors affect it [5, 29]. To start with, most commercially available UAVs are remotely controlled using the ISM band which is also shared by the WSN. This will result in a substantial interference. Secondly, moving UAVs may have difficulty establishing steady links. Even when they are hovering at one spot, establishing steady links may still be challenging due to wind and inherent vibration of the UAVs. The goal of this paper is to experimentally investigate the effect of these factors. We deployed a WSN consisting of 9 nodes in an open field next to a forest and use a UAV to interact with the network. We considered three different scenarios. In the first and the third scenarios, the UAV hovers at one spot approximately in the middle of the network, regarded from a top perspective view. In the second scenario, the UAV moves in a square trajectory. In the first two scenarios a node deployed on the UAV received packets from the nodes on the ground whereas in the third scenario, the node on the UAV broadcast packets in burst and the nodes on the ground receive the packets. Our experiment results reveal that the links interfacing the UAVs with the WSN were of poor quality. In none of the experiments could we achieve a packet success rate exceeding 50 %.

The contributions of our work are summarized as follows:

- A comprehensive, experimental characterization of the air/ground links in terms of RSSI, packet success rate, and consecutive success and failure.
- A probabilistic model which estimates the optimal time required for a UAV to collect data from a ground wireless sensor network.

The remaining part of the paper is organized as follows: In Section 2 we describe our experiment setting and discuss the experiment results. In Section 4, we review related work. Finally, in Section 5, we provide concluding remarks and outline future work.

2 EXPERIMENT

We selected a big open space next to a forest as our test field. In this space 9 RE-Motes[1] were deployed forming a grid topology (as shown in Fig. 2). Another node was attached to a DJI Mavic 2 Enterprise drone[2]. We conducted three experiments to achieve different goals (ref. to Table 1 for the configurations). In all the experiments, the transmission power was set to 7 dBm which is the highest power for an RE-Mote. The communication channel was 26 which is orthogonal to the backbone WiFi control channel we set up for controlling the experiments and for dynamically changing experiment parameters. Furthermore, most communication protocols in WSNs take Channel 26 as their default setting [8][28], and has been proofed to be the most robust against cross technology – like WiFi and Bluetooth – interference [14][22][2]. In the first two experiments, the node on the UAV was configured as a receiver and the ground nodes were transmitters (each node transmitted 1000 packets in burst with an inter-packet interval of 20 ms). In the last experiment, the node on the UAV was configured as a transmitter (totally transmitting 3000 packets) and the ground nodes as receivers. In the first and the third experiments the UAV was hovering at one spot all the time, approximately at 10 m hight from the ground, whereas in the second experiment it was moving in a

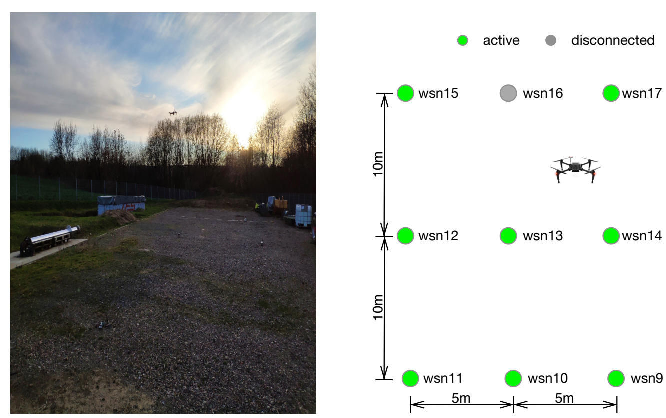


Figure 2: The WSN deployed to investigate the link quality interfacing the ground network with a UAV.

Table 1: Experiment parameters

ID	packets	transmitter	UAV action
exp1	1000	ground nodes	hovering, ca. 10 m high
exp2	1000	ground nodes	moving, square trajectory
exp3	3000	node on the UAV	hovering, ca. 10 m high

[1] https://zolertia.io/product/re-mote/
[2] https://www.dji.com/de/mavic-2-enterprise

square trajectory ($wsn11 \rightarrow wsn15 \rightarrow wsn17 \rightarrow wsn9 \rightarrow wsn11$), again approximately from the same 10 m hight.

2.1 Link Quality Parameters

For each packet transmission, the background noise – before each transmission and after each reception–, received signal strength indicator (RSSI), link quality indicator (LQI), Acknowledgement, timestamps, and packet sequence number were recorded. In order to avoid packet collision between the ground nodes, each node was allocated a dedicated time for packet transmission. This excludes the MAC protocol of the WSN from being responsible for the quality of the ground-to-air link.

2.2 Background Noise

The background noise refers to a steady presence of an appreciable signal level at the antenna of a node in the absence of any packet transmission. Fig. 3 displays the background noise during the three experiments. Compared with our previous experience with mobile robots [28], the background noise in the UAV experiments is more dynamic. According to the DJI Mavic 2 Enterprise specification, the remote controller uses DJI long-range transmission technology OcuSync 2.0 [13], which operates at 2.4 GHz and 5.8 GHz. The operation frequency is automatically selected at runtime to achieve the best SNR. The selection operation is typically completed within a single video frame (in the order of milliseconds). The 2.4 GHz used in DJI belongs to the same ISM band to which also the IEEE 802.15.4 specification belongs. Hence, the noise perceived by the RE-Motes is partly due to the operation of the remote controller in the 2.4 GHz channels.

2.3 Packet Reception Ratio

The packet reception ratio is the ratio of the number of received packets to the number of transmitted packets and is a coarse measure of the reliability of a channel. Coarse, because it does not take short-term link quality fluctuations into consideration. For all the three experiments, the packet reception ratio was below 0.5 (as shown in Fig. 4). Particularly, the nodes wsn9, wsn13, and wsn15 in exp1 experienced very poor packet success rates (0.159, 0.144, 0.147, respectively).

2.4 Fluctuation of the RSSI

The RSSI is widely regarded as the most unstable link quality indicator, particularly in indoor environments [9, 15, 23]. Our analysis, however, produced mixed results. When the UAV was stationary, the RSSI of most received packets could be regarded as stable, whether the packets were transmitted from the UAV to the ground nodes or vice versa. Even when the RSSI values showed fluctuation for some nodes, they were nonetheless within an appreciable range. Fig. 6 displays the RSSI values of received packets originating from three ground nodes. The RSSI values of the packets originating from wsn13 fluctuated but the range was within -15 dBm. When the UAV was flying, the RSSI values of the received packets fluctuated appreciably, but now from the fluctuation pattern it was possible to estimate the relative distance of the UAV with respect to the ground nodes. This can be seen in Fig. 7 where we plotted the RSSI values of the received packets originating from two diametrically opposite placed nodes. As can be seen, not only appear the RSSI values to be dependent on the relative position of the UAV with respect to the ground nodes, but also it is possible to estimate the UAV's speed of flight and the number of rounds it made during packet transmission.

The RSSI values can indicate whether the wireless channel interfacing the UAV with the WSN can be regarded as symmetric. This knowledge is vital to manage transmission power. If the channel is asymmetric, nodes can use different transmission power levels to save energy. Similarly, the transmission power can be adapted to the state of the UAV (hovering, flying).

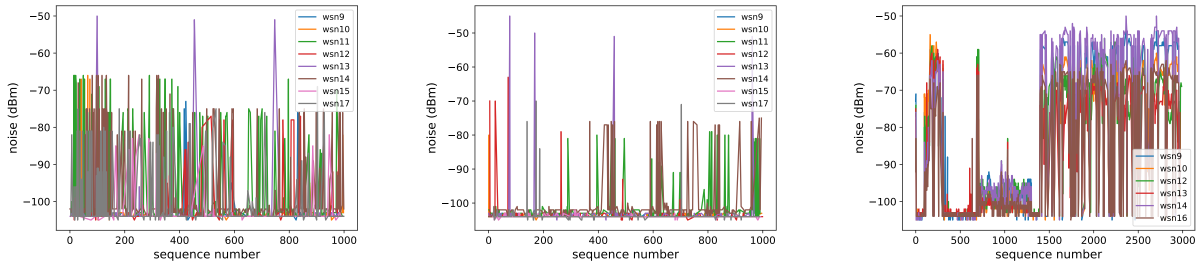
Fig. 5 displays the empirical density functions of the RSSI values of received packets in the three experiments. The first and the third experiments were different only in the direction of packet transmission and the results seem to suggest that the channels could not be taken as symmetric. The same can be said of the second experiment in which the UAV was flying. In general, however, from the distributions, it can be concluded that the RSSI values were appreciably good in all the experiments. This observation begs the following question: If the RSSI of received packets suggest that the wireless channels were good where does then the high packet failure come from? The only reasonable answer is the one we gave above in Sec. 2.2, i.e., interference from the remote control of the UAV.

2.5 Packet Success Rate

An interesting aspect to investigate would be how much the background noise and the received signal strength affect the successful delivery of packets independent of the activity and relative distance of the UAV. One of the problems to achieve this goal is that the RSSI values of lost packets cannot be known and in the absence of this information it is impossible to establish the complete statistics. A plausible solution would be to approximate them:

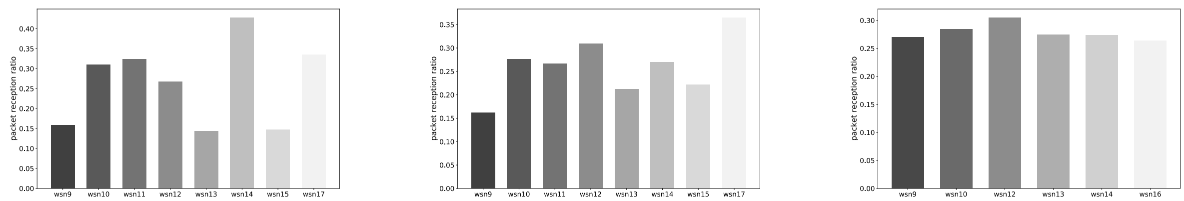
- For every 100 packets a node transmits in succession, we calculate the packet success rate as the ratio of the received packets to the transmitted packets for that slot.
- We sample the background noise before the transmission and after the reception of each packet and average it for each slot.
- We calculate the average RSSI values of the received packets and assign this value as the RSSI value of the slot.
- We correlate the average RSSI values with the packet success rate.
- The same steps are taken to correlate packet success rate with background noise.

Fig. 8 displays the relationship between the noise and packet success rate. The statistics takes into account all the packet transmitted and received in the three experiments. From the figure it is apparent that there is a strong correlation between the two quantities. The smaller the background noise the higher is the packet success rate. Similarly, Fig. 9 displays the relationship between RSSI and packet success rate. Unlike the first case, one can see here that there is no apparent correlation between the two quantities suggesting that the success or failure of packet transmission did not much depend on specific RSSI values, which again confirmed the observations we made in the previous subsections.



(a) exp1 (b) exp2 (c) exp3

Figure 3: Comparison of the background noise experienced by the wireless sensor nodes in the three experiments.



(a) exp1 (b) exp2 (c) exp3

Figure 4: The packet reception ratios of the three experiments.

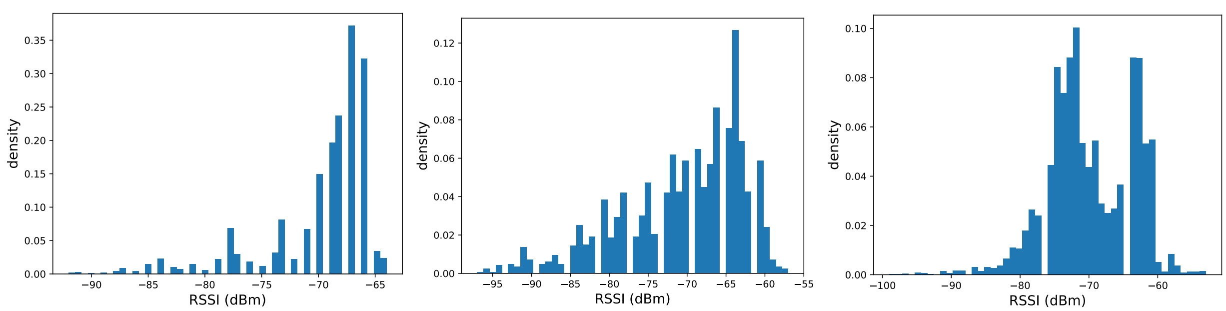


Figure 5: The probability distribution of the RSSI values of received packets from the three experiments. Left: Ground node transmitting, UAV hovering at one spot. Middle: ground nodes transmitting, UAV flying in a square trajectory. Right: Node on the UAV transmitting, node hovering at one spot.

2.6 Consecutive Success and Failure

How long a wireless link stays stable in a given state can be indirectly determined by counting the number of packets successively delivered or failed. This metric is useful for scheduling and coordinating packet transmission. For example, if the average number of consecutive failures can be estimated, nodes can refrain from contending to seize the medium for a specific amount of time. Similarly, if the average number of consecutive success can be estimated, communication between the UAV and the ground gateways can take place through burst communication. The duration of the burst transmission can be determined from the duration of the consecutive success. The statistics of consecutive failure and success are channel dependent, but they can be combined to give an overall picture of a specific deployment scenario. Fig. 10 summarises the statistics for our deployment. Negative numbers signify consecutive failure whereas positive numbers signify consecutive success. From the figure it can be deduced that in our deployment every other packet was destined to succeed or fail.

3 ESTIMATION OF DATA COLLECTION TIME

The flight time is one of the critical aspects which limit the scope of employing a UAV for data collection. This aspect is particularly critical considering the limited battery life of the UAVs and the poor packet reception ratio of the ground-to-air link. As we already pointed out, the packet reception ratio in turn depends on many factors including the deployment environment, the placement of nodes, and the wireless interface between the UAV and its remote control station. In general, the packet reception ratio cannot be known in a deterministic sense. On the other hand, without the

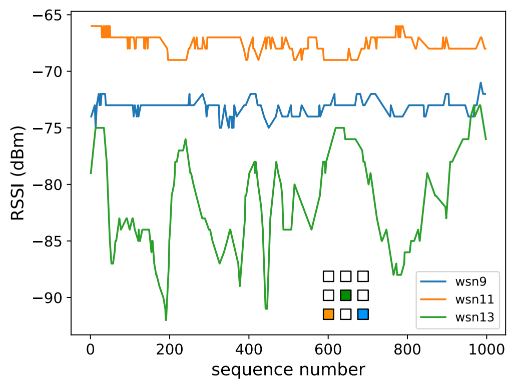


Figure 6: The fluctuation in the RSSI values of received packets. The ground nodes transmitted the packets and the UAV which was hovering above received the packets. The graph indicates the relative position of the sensor nodes.

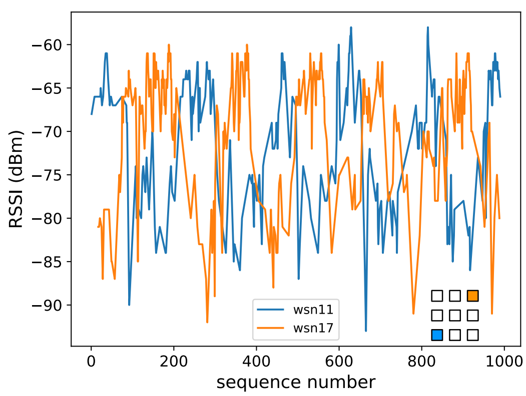


Figure 7: The fluctuation in the RSSI values of received packets. The ground nodes transmitted the packets and the UAV which was flying above in a square trajectory received the packets. The graph indicates the relative position of the sensor nodes.

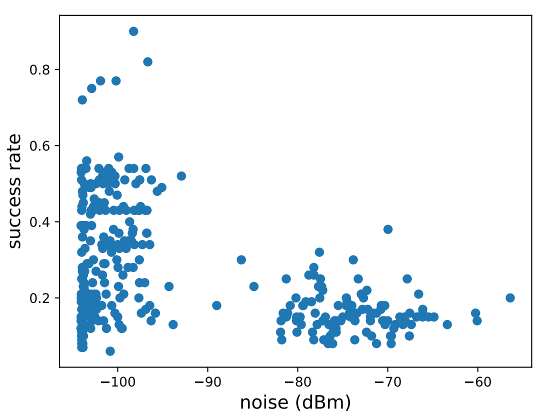


Figure 8: The correlation between packet success rate and background noise.

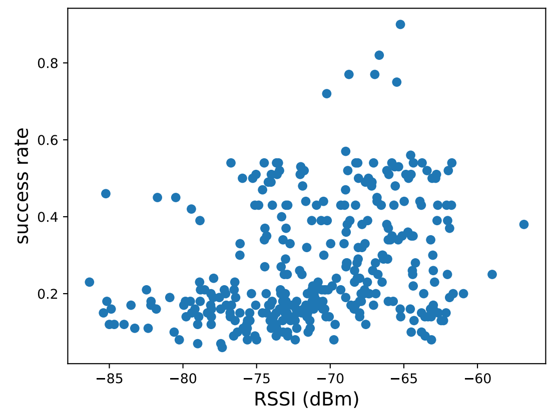


Figure 9: The correlation between packet success rate and RSSI.

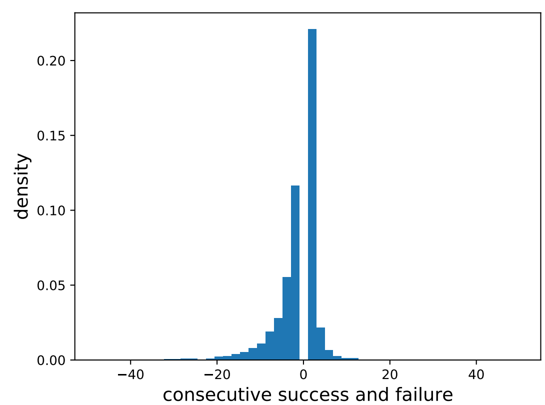


Figure 10: Statistics pertaining to the number of packets successfully transmitted and consecutively failed.

knowledge of the packet reception ratio, it is difficult to make a reliable decision as regards the rate at which the sensors should be sampled and the duration of packet transmission between the ground gateways and the UAV. In this section we develop a probabilistic model to relate the number of packets that can be delivered to a UAV with a certain degree of confidence and the corresponding time needed to deliver the packets, assuming that the UAV interacts with a single gateway at a time.

Suppose a gateway takes on average T amount of time to transfer n number of packets to a UAV. This is a rough estimation of the

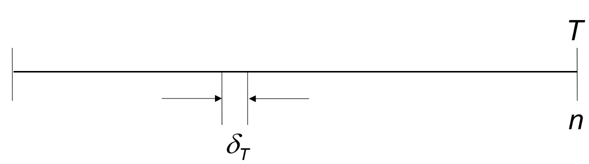


Figure 11: Determining the time window required to successfully deliver a packet.

wireless link because it disregards how the link fluctuates and how many packets were successfully delivered or failed in succession. The packet transmission rate for this model can be expressed as:

$$\mu = \frac{n}{T} \tag{1}$$

The probability of successfully transmitting a single packet in the time window δ_T in Fig. 11 depends on the size of the window, the bigger the size, the higher is the probability. It reaches the value of unity as the size approaches to infinity. Hence, we can express the probability as:

$$p = \frac{\delta_T}{T} \tag{2}$$

Since we already assumed that n packets had been transmitted, we can divide T into n slots. But since the wireless channel is probabilistic, we may not be able to transmit the same number of packets for the same duration T if we repeat the experiment. However, we can estimate the number of packets we can transmit using the past statistics. Alternatively, we can determine the probability of successfully transmitting k packets in the same time span T. Using the binomial distribution, this can be expressed as:

$$P(k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{3}$$

Substituting Equation 2 in Equation 3 yields:

$$P(k) = \binom{n}{k} \left(\frac{\delta_T}{T}\right)^k \left(1 - \frac{\delta_T}{T}\right)^{n-k} \tag{4}$$

If we expand the binomial term in Equation 4 and make use of Equations 1, we get the following expression, which we can latter simplify:

$$P(k) = \frac{(n-1)\cdots(n-(k+1))}{k!n^k} (\mu\delta_T)^k \frac{\left(1 - \frac{\mu\delta_T}{n}\right)^n}{\left(1 - \frac{\mu\delta_T}{n}\right)^k} \tag{5}$$

Notice that we have substituted T with n/μ. Furthermore, if we factor all the ns in the binomial expression and let n approach to infinity, the result will be 1:

$$\lim_{n\to\infty} \left(1 - \frac{1}{n}\right) \cdots \left(1 - \frac{(k+1)}{n}\right) = 1 \tag{6}$$

Similarly,

$$\lim_{n\to\infty} \left(1 - \frac{\mu\delta_T}{n}\right)^k = 1 \tag{7}$$

but

$$\lim_{n\to\infty} \left(1 - \frac{\mu\delta_T}{n}\right)^n = e^{-\mu\delta_T} \tag{8}$$

Consequently, what is left of Equation 5 as n approaches to infinity is a Poisson distribution:

$$P(k) = \frac{(\mu\delta_T)^k}{k!} e^{-\mu\delta_T} \tag{9}$$

The significance of Equation 9 is that it is now possible to associate a degree of confidence to packet collection. Moreover, it sets a trade-off between the degree of confidence and latency, because the number of packets which can be collected depends on the time apportioned for each packet. The term μ is a model of the deployment environment and can be determined empirically.

In order to determine the optimal δ_T maximising the probability of k, we can differentiate the equation with respect to δ_T and set the result to zero[3]:

$$\begin{aligned} \frac{\partial P(k)}{\partial \delta_T} &= \frac{\mu^k}{k!} \frac{\partial}{\partial \delta_T} \left(\delta_T^k e^{-\mu\delta_T}\right) = 0 \\ &= \frac{\mu^k}{k!} \left(k\delta_T^{k-1} e^{-\mu\delta_T} - \mu\delta_T^k e^{-\mu\delta_T}\right) = 0 \end{aligned} \tag{10}$$

Further factoring out the common terms in the middle expression and moving them to the right term yields:

$$\frac{k}{\delta_T} - \mu = 0 \tag{11}$$

From which we have:

$$\delta_T = \frac{k}{\mu} \tag{12}$$

Thus, according to Equation 12, once the deployment environment (i.e., μ) is determined empirically it is possible to estimate (1) the optimal number of packets that can be transmitted in a given period and (2) the optimal duration to collect K number of packets successfully.

4 RELATED WORK

In the last decades, a substantial number of experiments have been conducted to investigate the characteristics of low power wireless links [2, 22], but only a few of them focus on aerial wireless sensor networks (AWSN). In [1], the authors performed three categories of experiments to study the characteristics of IEEE 802.15.4 compliant radios in three different communication links: ground-to-ground, ground-to-air and air-to-ground. In their experiments, The transceivers were attached to hexacopers which were flying at different heights and distances from the ground node. They showed that the link quality in terms of RSSI is irregular for different antenna orientations and the link quality is affected predominantly by shadowing, path fading and reflection factors.

In [11], the authors employed a fix-wing UAV with a TI CC2530 radio installed and deployed another TI CC2530 transceiver on the ground to study the link quality of air-to-ground communications. They concluded that within the communication range (ca. 150 m), the packet success rate could reach 80% while the RSSI value was above −90 dBm. This observation agrees with a previous study on stationary deployments [2]. In [4], the authors proposed a wireless environmental monitoring system by using UAVs to collect ground data. To evaluate the communication range of the ground-to-air link, they utilized two IEEE 802.15.4 compliant Xbee radios, one as a transmitter, deployed on the ground, and the other as a receiver, attached to a UAV. They showed that the best link quality in terms of RSSI and packet success rate could be achieved when the flight height was around 10 to 12 meters and the transmitter was 30 meters away from the receiver.

Unlike the previous studies which were based on a single pair of transmitter and receiver, Nekrasov et al. [16] deployed four Xbee3 2.4 GHz transmitters in a line on the ground with different environmental configurations and two receivers attached to a DJI Matrice

[3] Recall that $\frac{\partial}{\partial x}(f(x)g(x)) = \frac{\partial f(x)}{\partial x} g(x) + f(x)\frac{\partial g(x)}{\partial x}$

100 quad-copter with orthogonal antenna settings (one is horizontal and the other is vertical to the ground). They observed that the link quality in terms of RSSI is almost the same for both antenna settings (less than 1 dB difference by mean values). However, the packet success rates are affected dramatically by the orientation. When the UAV flied at 76 m height and 100 m horizontal distance away from the transmitters, the packet success rate of horizontal setting can still be above 75% while it dropped less than 25% with vertical one. To achieve a better communication performance, the author suggested that the transmitter deployment, the altitude of UAV, antenna orientation of the receiver should be optimized.

In [26], the authors proposed an AWSN consisting of two fixed wing UAVs, three LoRa sensor nodes and one base station. All the sensor nodes transmit their data periodically to the base station in a star topology. The two UAVs were used to collect data from the base station by a specific reliable protocol. In their experiments, the authors only measured the RSSIs of the packets received by the UAVs and the base station as a function of distance.

In [17], a quad-copter is used to enhance the communication range of water sensor networks. The UAV is controlled by a remote ground station via IEEE 802.15.4 compliant radio and integrated a secondary IEEE 802.15.4 compliant radio to communicate with the water sensor networks. The authors compared the packet success rates between UAV-to-water and water-to-water links. They concluded that with the help of the UAVs, the communication range of the water sensor network could be extended to 212 meters while achieving a packet success rate of 75%.

In [24], the authors proposed a novel AWSN system for crop monitoring. In their experiments, three clusters of TelosB nodes (totally 10 nodes) were deployed in fragmented farming areas to monitor the temperature, humidity and light. A UAV equipped with a TelosB node is used as the mobile data collector. The UAV is flying at three different heights to evaluate the link quality in terms of signal quality and packet loss rate. By comparing the link quality between air-to-ground and ground-to-ground links, they concluded that employing UAV to collect data could improve the average signal quality by 19% and reduce the packet loss rate by 70%.

To compare the data collection performance by ground vehicle and UAV, Jeong et al. [12] conducted an experiment in woods. They deployed a TelosB node as a transmitter in the woods which was approximately 40 m away from a road. A vehicle and one quad-copter equipped with TelosB motes were employed to collect data at five predefined locations on the road. The receiver on the vehicle was installed 2 m above the ground and the UAV was flying at 15 m and 10 m heights. In their results, the authors showed that at all five locations the UAV data collector outperformed the ground vehicle in terms of packet success rate and RSSI. More specifically, the packet success rate of ground vehicle is around 50% while that of UAV is above 90%. The RSSI from the UAV collector is 5 dB higher than the RSSI from the ground vehicle on average.

5 CONCLUSION

In this paper we presented experiment results concerning the quality of a wireless link interfacing a wireless sensor network with a UAV. This type of deployment can be useful to inspect and monitor dangerous or inaccessible places. Our experiments results showed that even though the signal quality of most received packets was good the packet reception ratio (the ratio of total received packets to the total transmitted packets) was below 50 %. We investigated the background noise experienced by each communicating sensor node and the number of packets successfully delivered or failed in succession to determine the reason behind the poor packet reception ratio. Our analysis suggests that the main cause is an interference arising from the UAV's remote controller which shares the ISM band with the wireless sensor network.

This motivates the MAC layer protocols managing the media shared by the wireless sensor networks and the remote controller should be optimized jointly.

An interesting aspect we observed concerns the activity of the UAV. From the evaluation of the RSSI of received packets it was possible to discern whether the UAV was hovering or flying. When it was flying, it was possible to locate its approximate position with respect to the ground nodes.

In this initial Work, our investigation was based on Channel 26, which is the most commonly used channel in WSNs. We chose this channel because it is considered to be the most robust channel against competing cross technologies operating in the ISM band. However, the air to ground link suffered from a serious interference arising from the UAV's remote controller, as can be seen from the poor packet success rates in all our experiments (below 50%). In the future, we are planning to conduct more comprehensive experiments to investigate the impact of cross technology interference in different channels and how it can be overcome.

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