A Link Quality Estimation Model for a Joint Deployment of Unmanned Aerial Vehicles and Wireless Sensor Networks

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***Abstract*—In the past two decades, several applications have been proposed for Wireless Sensor Networks (WSNs). Some of these applications, such as habitat monitoring, active volcano monitoring, and toxic gas detection, exclude the involvement of human presence because the environments are either dangerous, inaccessible, or too extensive. The scope of these applications can be extended if the ground networks are assisted by a network of Unmanned Aerial Vehicles (UAVs). Paramount to this is the stability of the wireless links the UAVs establish with the ground nodes. Lossy and unstable links are costly to maintain the UAVs may exhaust their batteries prematurely. In this paper, we experimentally investigate the stability of aerial-to-ground links and propose a stochastic model to predict link quality as a function of time. The model can be used to estimate goodput, determine mission duration, and estimate short-term link connection and disconnection durations.**

***Index Terms*—Wireless sensor networks, UAV, link quality fluctuation, Poisson Process, Internet of Things**

I. INTRODUCTION

The use of Unmanned Areal Vehicles (UAVs) in supply-chain [1], surveillance and military operations [2], precision agriculture [3], search and rescue [4], and many other applications, is becoming widespread. These applications involve extensive, inaccessible, remote, or dangerous areas in which human presence is either undesirable or deemed to be dangerous [5]. Some of these applications require precision sensing on the ground for which the UAVs are ill equipped. For example, in precision agriculture, the application of pesticides and herbicides requires a micro-scale map of the temperature and humidity distribution which has to be done with the help of sensor networks [3], [6]. Likewise, monitoring the magnitude and extent of toxic gases following a chemical disaster – fires, explosions, leakages or release of toxic or hazardous materials – requires the deployment of ground sensors [7], [8]. Similar applications such as determining the extent of damage following the collapse of complex buildings, bridges, or underground mines require such devices as wireless cameras, microphone, and CO_2-sensors to detect human presence; and pH and oxygen sensors to estimate how long the environment supports human life [9].

In such scenarios the joint deployment of wireless sensor networks (WSNs) and Unmanned Aerial Vehicles (UAVs) enhances performance and extends the scope of a deployment [10], [11]. However, the success of this type of deployment depends on many factors including the reliability of the wireless links connecting the nodes with the UAVs and with one another, which in turn, depends on many environmental factors. In this paper we propose a stochastic model for characterising the quality of areal links connecting a wireless sensor network with a UAV. Our model is based on extensive experiments and enables to estimate both long-term and short-term link stability and can be used to achieve the following goals:

- Estimate overall goodput.
- Estimate a UAV's mission duration (alternatively, the energy demand of the UAV for a set duration).
- Identify the best medium access strategy.

The remaining part of the paper is organized as follows: In Section II we describe our typical deployment features and experiment settings. In Section III, we propose a stochastic Poisson model to associate link quality with time and estimate long- and short-term link stability. In Section IV, we validate our model with experimental datasets. In Section V, we review related work. Finally, in Section VI, we provide concluding remarks and outline future work.

II. DEPLOYMENT FEATURES

Several decisions have to be made when a joint deployment is carried out. Assuming that the size of the sensor network and the number of UAVs are determined by the application's requirements and the deployment setting, the next important decision to be made is how to coordinate between the sensor network and the UAVs; between the UAVs; and between the sensor nodes themselves. Both to maximize performance and to reduce Cross Technology Interference (CTI) [12], [13], [14]), the UAVs should cover none-overlapping regions. This also simplifies the data collection and command dissemination assignments. If the purpose of the UAVs is exploration or to augment visual perception, coordination is relatively simple. If, on the other hand, a significant amount of sensor data have to be extracted from the environment in real-time or near real-time, then establishing efficient, stable, and reliable links between the WSN and the UAVs is critical.

A. Coordination

Typically, a WSN consists of several wireless sensor nodes one of which is designated as a base station. The predominant network traffic flow is from the sensor nodes to the base station. The topology of the network can be either flat (i.e., with no hierarchy amongst the nodes) or hierarchical. In the first, all the nodes play the same roles (sensing, data aggregation, and packet forwarding) whereas in the second, the network is divided into clusters and each cluster is represented by a cluster head. The cluster heads coordinate data transmission within their cluster, aggregate data, and communicate the result to the base station either directly or via other cluster heads whereas the role of child nodes is to sense and report to their cluster head.

Interaction between the wireless sensor network and the UAVs is easier when the network is hierarchical. In case of multiple UAVs, they can divide the region into non-overlapping clusters, each UAV interacting with a particular region. In case of a single UAV deployment, either it flies between the cluster heads, interacting with one of them at a time. If the network has a flat topology, multiple routes from the source nodes to designated gateways can be defined. Once the gateway nodes are identified, establishing routes using peer-to-peer routing protocols such as Ad-hoc On-Demand Distance Vector (AODV) Routing [9] is possible.

Irrespective of the specific network topology, the quality of the wireless links the gateways establish with the UAVs are crucial for data collection and for the UAVs to utilise energy efficiently. Unfortunately, these links are affected by many factors [15], the most significant of which are fading and CTI. Unless the sensor nodes and the UAVs are jointly developed from the outset with specific goals in mind, their network interfaces will be different. Indeed, most practical deployments will involve off-the-shelf UAVs and sensor nodes. The UAVs are controlled remotely using the ISM band which is also shared by the WSN. This will result in a substantial interference. Furthermore, moving UAVs may have difficulty establishing and maintaining steady connections. Even when they are hovering at one spot, maintaining steady links is challenging due to wind and inherent vibrations of body parts.

B. Communication

In the IEEE 802.15.4 specification [16], a total of 16 channels are available in the $2.4\,\mathrm{GHz}$ band. These channels are numbered 11 to 26. Each channel has a bandwidth of $2\,\mathrm{MHz}$ and separated from its neighbour channels by a $5\,\mathrm{MHz}$ guard-band. In the presence of a UAV, some of them are significantly affected by a CTI. Even though the IEEE 802.15.4 does not offer a physical layer solution for dynamic channel selection and frequency hopping, it, nevertheless, offers a link-layer solution to enable a dynamic frequency hopping to mitigate CTI and frequency-selective fading [17], [18]. Some of the commercially available radio chips, such as CC2538 [19], and operating systems (Contiki [20]) implement the specification to some extent. Strictly speaking, the proposed solution is pseudo-random, in that the hopping from one channel to another obeys a deterministic rule. This strategy can be counterproductive in a highly bursty environment, since the duration a transmitter stays in one channel and the transition between channels are predetermined, not taking the current state of the channels into consideration. Its performance can be enhanced if the rule is based on interference statistics.

C. Medium Access

The efficiency of medium access in a coordinated deployment is essential to make sure that the UAVs do not waste energy aimlessly. Conventional medium access control mechanisms, such as CSMA/CA, may not perform optimally in bursty environments, but combined with a TDMA and frequency-hoping mechanism, will enhance channel utilisation and enables individual nodes to switch-off their radios when a link is bad. Since the energy supply of the UAVs is the most critical resource to conserve, the UAVs can coordinate the allocation of time slots to the ground gateways and cluster heads.

D. Limited Energy

One of the formidable challenges in employing UAVs is their limited energy supply. In case the UAVs carry additional sensor nodes which they supply with energy, the duration of flight can be severely constrained. Windy environments and protruding structures imped smooth flight and navigation, further exacerbating the energy consumption. In order to plan and effectively execute UAV deployment, it is essential to estimate the mission duration. One way to achieve this is to express data collection as a function of time.

III. LINK QUALITY MODEL

Experimental studies reveal that low-power wireless links are bursty [21], [22], [23], [11] in that even in the absence of an appreciable CTI, they experience frequent transitions between short-term connected and disconnected states. When UAVs are involved, the CTI arising as a result exacerbates this condition, thereby affecting the performance of both the UAVs and the WSN. A quantitative model describing the temporal characteristics of the wireless links is, therefore, vital for optimising the design and configuration of communication protocols; scheduling packet transmission; defining sleeping schedule; and estimating the mission duration of the UAVs.

A. Lossy Low-Power Links

In this subsection, we shall demonstrate that the quality of the wireless links interfacing a UAV with ground sensor nodes can be modelled as a *time-varying* stochastic process. Our model is based on actual experiments we carried out in an outdoor environment. Our deployment consisted of nine wireless sensor nodes forming a grid topology in an open field next to a forest. The space between the nodes was $5\,\mathrm{m}$ row-wise and $10\,\mathrm{m}$ column-wise. A DJI Mavic 2 Enterprise drone[1] carrying two wireless sensor nodes hovered above the sensor network at various heights. The transceivers of all the nodes were IEEE 802.15.4 compliant. fig. 1 displays our deployment setting.

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[1] https://www.dji.com/mavic-2-enterprise

Fig. 1. The deployment setting.

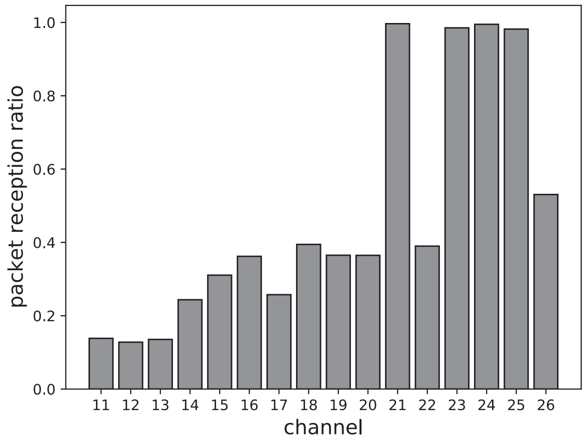

Fig. 2. The packet reception ratio for one of the sensor nodes.

Fig. 2 shows the average Packet Reception Ratio – the ratio of the successfully transmitted packets to the overall transmitted packets – for one of the experiments we carried out. In this experiment, one of the sensor nodes carried by the UAV transmitted 2000 packets in burst in each of the available channels (altogether 16 channels) with an inter-packet interval of 8 Hz and a transmission power of 7 dBm. From the figure it can be seen that the receivers experienced a significant packet loss when a UAV is employed. The corresponding average background noise (measured before the transmission of a packet and after the reception of a packet) is shown in Fig. 3.

B. Link Quality as a Stochastic Process

Fig. 4 shows the packet reception pattern of two ground nodes when communicating in two different channels (Channels 11, and 13).

Lossy links affect not only the quality of the interaction between the ground nodes and the node carried by the UAV, but also the flight time of the UAV. The latter is affected in two ways:

- The retransmission of packets requires extra flight time.

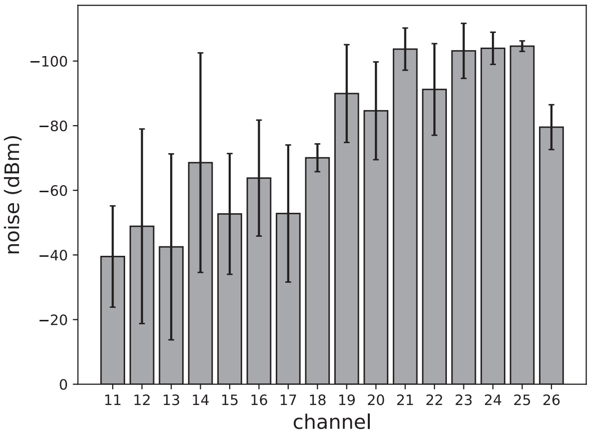

Fig. 3. The background noise induced on the 16 channels by a Cross Technology Interference.

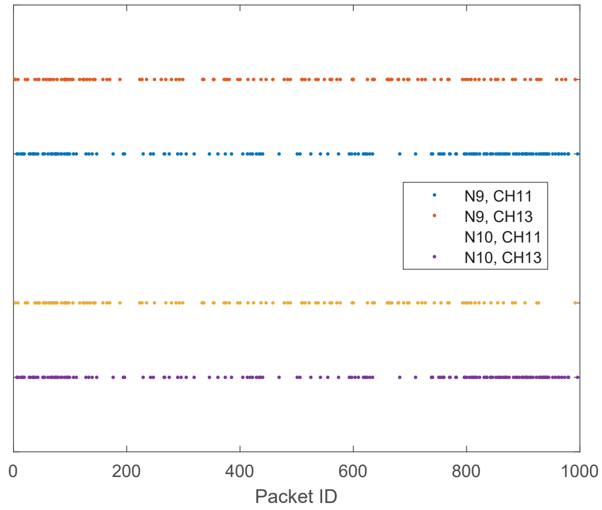

Fig. 4. Sequences of ACK packets received by two ground nodes in two different channels.

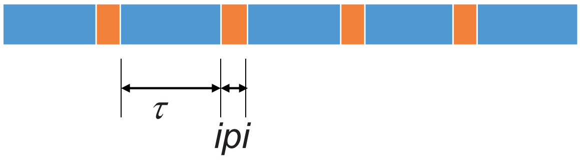

Fig. 5. Packet transmission in burst. τ, is the ideal time a transmitter takes to transmit a single packet. An ipi is required, among others, for the transceiver to switch between transmission and reception modes.

Fig. 6. Associating a probability to packet transmission in a lossy link.

- In case the UAV supplies the nodes with energy, then packet retransmission entails additional energy burden.

In order to estimate (1) the time the UAV requires to collect a given number of packets from the ground nodes, (2) the energy reserve of the UAV, and (3) the duration of connected and disconnected (short-term) states, it is important to express packet reception as a function of time. One way to achieve this is to regard the wireless link as a stochastic process.

When a node transmits packets in burst, the time between two successive packets is called the inter-packet interval (ipi) – measured in seconds. This time is required for the transceiver to switch between receiving and transmitting modes and for the operating system to process the outgoing and incoming packets through the different communication stacks. Suppose the ideal time a node requires to successfully transmit a single packet is τ seconds. In order to transmit W number of packets, the node requires $T = W\tau + (W-1)ipi$ seconds (ref. to Fig. 5). Alternatively,

$$W = \frac{T - ipi}{\tau + ipi} \approx \frac{T}{\tau + ipi} \tag{1}$$

With a lossy link, however, the node successfully transmits n number of packets ($n < W$). The relationship between T and n can be expressed as $n = \mu T$. For an observation period T which is long enough, μ can be taken as an expression of the long-term quality of the link. Suppose, however, we are interested in a small time window $\Delta_T > \tau$, arbitrarily located between $[0, T]$ as shown in Fig. 6. The probability of successfully transmitting a single packet in this window for this particular channel depends on its relative width, so that we can express it as:

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

One can view p as the probability of observing a single packet in Δ_T while all the other packets are received outside of this window. The probability of successfully receiving k number of packets in that same time window is given as:

$$P(k) = \binom{n}{k} \left(\frac{\Delta_T}{T}\right)^k \left(1 - \frac{\Delta_T}{T}\right)^{n-k} \tag{3}$$

If we express $\lambda = np$ (a portion of the W number of packets successfully transmitted in T), the above equation can be expressed as:

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

Expanding the above term and factoring out n from the binomial expression yields,

$$P(k) = \frac{(1-1/n)(1-2/n)\cdots(1-(k+1)/n)}{k!}\lambda^k \frac{\left(1 - \frac{\lambda}{n}\right)^n}{\left(1 - \frac{\lambda}{n}\right)^k} \tag{5}$$

For a large number of packets, we have:

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

Similarly,

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

but:

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

Consequently, what is left of Equation 5 as n approaches to infinity is a Poisson distribution [24]:

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

If we double the time window, the value of p doubles accordingly. Hence, the probability of transmitting k number of packets in this window can be expressed as:

$$P(k) = \frac{(2\lambda)^k}{k!} e^{-2\lambda} \tag{10}$$

For any arbitrary time window, t, we have a Poisson stochastic process whose distribution can be expresses as:

$$P(\mathbf{x}(t) = k) = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \tag{11}$$

where $\mathbf{x}(t)$ is a time dependent stochastic process representing the number of packets a UAV collects using a particular lossy link in the interval $[0, t]$.

C. Channel Utilization

Equation 11 contains complete information about the channel it represents. Thus, the mean of $\mathbf{x}(t)$ – $E[\mathbf{x}(t)] = \lambda t$ – can be taken as the measure of the channel's utilization or goodput as a function of time. Similarly, the variance – $E\left[(\mathbf{x}(t) - \eta_x)^2\right]$ – can be taken as the measure of burstiness of the channel.

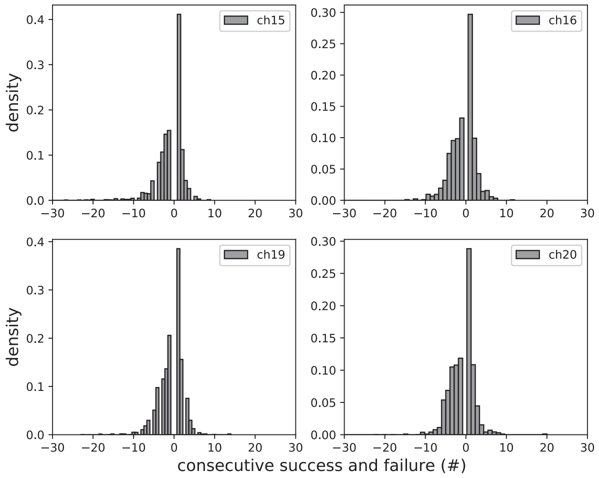

Fig. 7. The empirical distribution of the number of packets either successively transmitted (positive) or lost (negative) for one of the ground sensor nodes in four different channels. 2000 packets were used to establish the statistics.

D. Short-Term Channel Stability

In Section II we mentioned that a combination of TDMA and CSMA can be one of the medium access strategies. We also mentioned the need to estimate the duration of a time slot. A fixed duration applicable to all the nodes, regardless of which channel they use, may not be the efficient way. The duration of good and bad states can be determined from the statistics of $\mathbf{x}(t)$. Indeed, we have already said that the variance of $\mathbf{x}(t)$ expresses the burstiness of the channel. But the variance expresses a long-term characteristics.

The short-term channel statistics can be determined in different ways. One of the ways is to transmit packets in burst (as we have already done in our experiments) and observe the packet reception pattern at the other end by counting the number of packets received and lost in succession. The distribution functions we establish this way can be used to characterize short-term channel stability. The expected number of continuous success and continuous failure can be taken as the basis for computing the short-term stable durations of the channel which can be used to determine the size of a burst. Fig. 7 shows the distribution functions of four different channels for one of the sensor nodes, the plus sign signifying the number of packets successfully transmitted in succession whereas the minus sign signifies the number of packets failed in succession. As can be seen, more than $30\,\%$ of the time, the successful transmission of a single packet was always followed by the loss of another packet in almost all the cases, thus emphasizing the strong effect of CTI when a remotely controlled UAV operates near a WSN.

In order to mathematically express the above phenomenon, one can ask the following question: If a node transmits n number of packets successfully in $t >> n\Delta_T$, how many of them are transmitted in succession on average? Answering this question amounts to characterizing the short-term stability of the wireless link. In order to illustrate this aspect, suppose in the time interval $[0, t = 50\Delta_T]$, a node transmits 20 packets successfully, as shown in Fig. 8. Ideally, only 20 slots would suffice to transmit the 20 packets. In order to examine the short-term stability of the link, one can ask whether the 20 packets were transmitted in succession. To address this question, one can consider the first 20 slots only and count the number of packets received in this window and assign a probability to this condition. Fig 9 illustrate the different possibilities.

To characterize the link adequately, one should take the full statistics of $\mathbf{x}(t)$. To this end, we define the random variable $\mathbf{n}_i$ with $P(\mathbf{n}_i = 1) = p$ signifying the successful transmission of a packet in a single slot and $P(\mathbf{n}_i = 0) = q = (1 - p)$, signifying a failed transmission. Hence, given $\mathbf{x}(t)$, the short-term channel stability can be expressed as a random process (i.e., a function of time):

$$\mathbf{s}(t) = \sum_{i=1}^{\mathbf{x}(t)} \mathbf{n_i} \tag{12}$$

Similarly, the short term disconnected state of the link is expressed as:

$$\mathbf{f}(t) = \sum_{i=1}^{\mathbf{x}(t)} (1 - \mathbf{n_i}) = \mathbf{x}(t) - \mathbf{s}(t) \tag{13}$$

So, for example, $\mathbf{x}(t) = n$ and $\mathbf{s}(t) = k$ refers to the condition that given a node transmitted n packets in burst, k of them are transmitted in succession or with uninterrupted success. Determining the probability distribution functions of $\mathbf{s}(t)$ and $\mathbf{f}(t)$ – both of which are conditional random processes – is useful for characterizing the short-term link quality with any degree of confidence. Thus,

$$P(\mathbf{s}(t) = k) = \sum_{n=k}^{\infty} P(\mathbf{s}(t) = k | \mathbf{x}(t) = n)\, P(\mathbf{x}(t) = n) \tag{14}$$

When $\mathbf{x}(t) = n$ (i.e., when $\mathbf{x}(t)$ is fixed), the conditional probability inside the summation term of Equation 14 reduces to a binomial distribution for $0 \leq k \leq n$. With this in mind and substituting Equation 11 into Equation 14, we have:

$$\begin{aligned} P(\mathbf{s}(t) = k) = &\quad e^{-\lambda t} \sum_{n=k}^{\infty} \frac{n}{(n-k)!k!} p^k q^{n-k} \frac{(\lambda t)^n}{n!} \qquad (15)\\ = &\quad \frac{p^k e^{-\lambda t}}{k!} (\lambda t)^k \sum_{n=k}^{\infty} \frac{(\lambda q t)^{n-k}}{(n-k)!} \end{aligned}$$

Recalling that:

$$\sum_{k=0}^{\infty} \frac{x^k}{k!} = e^x \tag{16}$$

and rearranging terms, Equation 15 yields [24]:

$$P(\mathbf{s}(t) = k) = e^{-\lambda p t} \frac{(\lambda p t)^k}{k!} \tag{17}$$

Likewise,

$$P(\mathbf{f}(t) = m) = e^{-\lambda q t} \frac{(\lambda q t)^m}{m!} \tag{18}$$

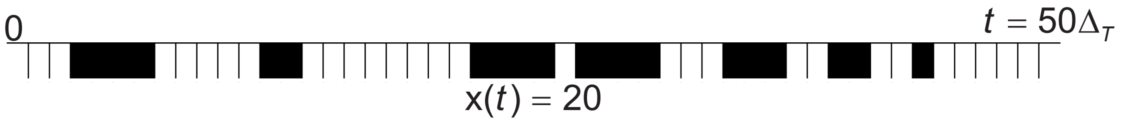

Fig. 8. The probability of successfully receiving 20 packets in $t = 50\Delta_T$s.

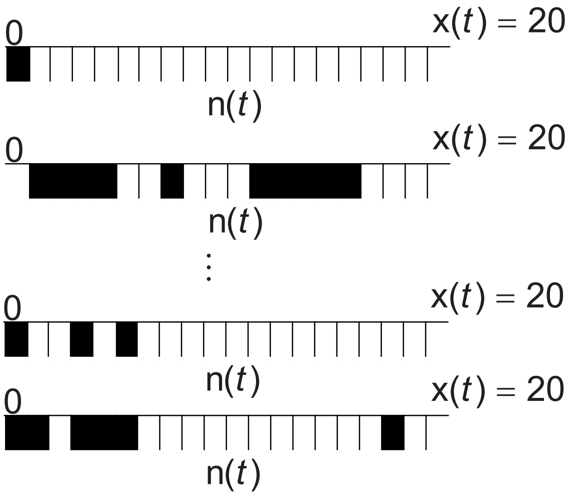

Fig. 9. Expressing the average number of packets that can be transmitted in a time window which is ideally sufficient for transmitting 20 packets.

IV. EVALUATION

The mathematical models we proposed in the previous section are useful to estimate various parameters including the amount of packets a UAV can gather in a set time. Conversely, given the amount of packets a UAV has to gather, we can estimate the time it needs. The short-term link stability models can serve at least two purposes. Firstly, they can be used to estimate the burst size should burst transmission be supported. For a TDMA MAC protocol, it can also be useful for determining the slot size. Secondly, they can be used to define a duty cycle (sleep duration) for the radios since it is wasteful to keep them active when a link is bad. In addition, the transition from a good state to a bad state, and vice versa, can be used to estimate the nature of a CTI and other types interferences and background noise.

A. Number of Packets Transmitted

One of the advantages of Equation 9 is that if one is interested to determine the average number of packets that can be successfully transmitted in the time interval $[0, t]$, then the answer is λt, since the mean of a Poisson random variable is the rate, which is λt. Moreover, for a given link, λ is fixed. Hence, the average number of packets becomes a linear function of time.

Fig. 11 displays the number of packets successfully received by three ground nodes in three different channels (Channels 11, 13, and 16). The UAV (as we already mentioned in the previous section) was broadcasting packets in burst for 2 s. Fig. 11 displays the actual and estimated (average) number of packets successfully transmitted up to time t. Table I lists the coefficients of determination – R^2 –, all of which save Channel 11 for the case of Node 13 resulted in $R^2 > 0.9$.

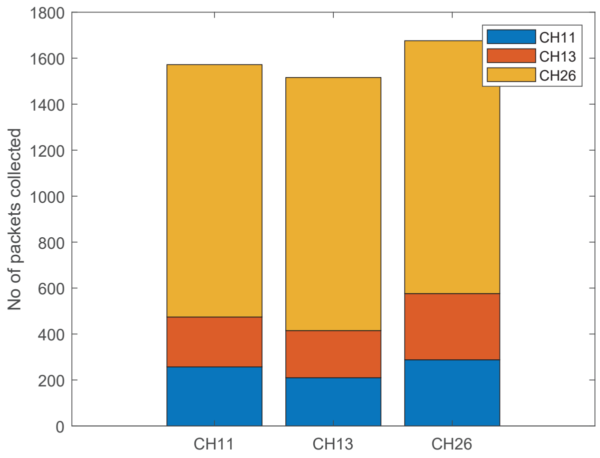

Fig. 10. The number of packets successfully received by three nodes in three different channels.

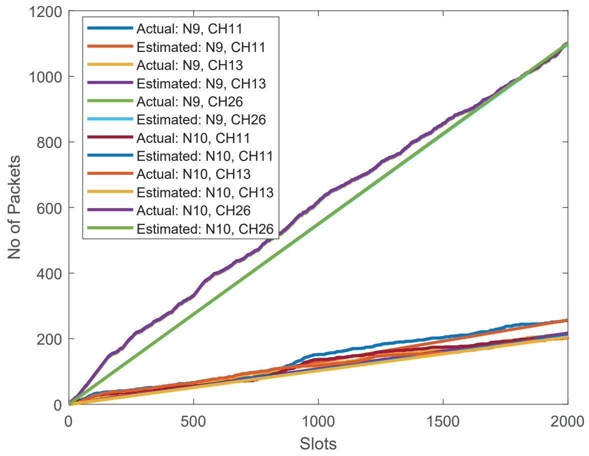

Fig. 11. The actual and estimated number of packets successfully received by Nodes 9 and 10 up to time t for Channels 11, 13 and 26.

B. Short Term Link Stability

The quality of a link can be expressed in terms of different metrics [25], [26], but as far as the mission duration of the UAV is concerned, the most important issue is the successful transmission of a packet. In a coordinated deployment, our experience shows that the most formidable challenge is interference arising from cross technology, most importantly, the

TABLE I

COEFFICIENT OF DETERMINATION (R^2) FOR THREE NODES AND THREE CHANNELS.

Nodes	CH11	CH13	CH26
Node 9	0.9710	0.9738	0.9752
Node 10	0.9355	0.9306	0.9734
Node 13	0.6734	0.9944	0.9746

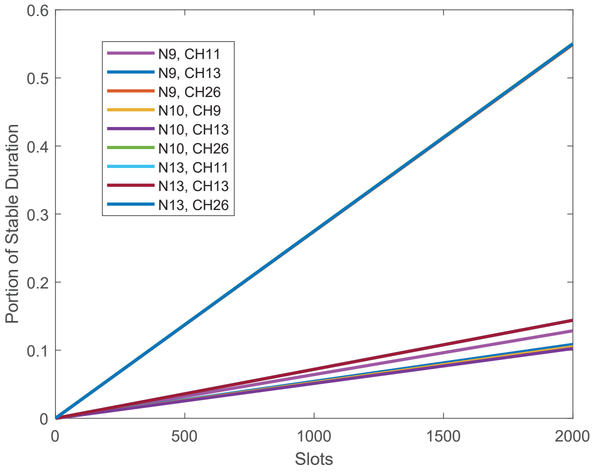

Fig. 12. The estimated portion of time channels 11, 13 and 26 stayed in a good state for Nodes 9, 10 and 13.

interference due to the remote control of the UAV. Significant interference can also arise if the UAV is carrying additional wireless devices enabling immersive experience (such as wireless cameras and other augmented reality devices) [27], [28].

Fig. 12 indicates the portion of packets (on average) which can be transmitted in succession in the time interval $[0, t]$ given the distribution of $\mathbf{x}(t)$. This figure gives a complementary view to the experiment based distribution in Fig. 7. There, one sees the long-term aspect of how many packets are transmitted in succession along with the associated probability. Here, one sees the characteristic of a link in the time interval $[0, t]$, for any arbitrary time $t < T$. The figure is produced using Equation 12.

V. RELATED WORK

Recent developments in low-power wireless and programmable devices have given rise to the Internet of Things which can support a wide range of applications. Typically, the networks these devices establish are impromptu, short-term, self-organising, low-power, and low-rate [29], [30]. Consequently, one of the challenges surrounding these networks is the reliability of the wireless links.

In the contexts of coordinated deployments involving wireless sensor networks and UAVs, existing studies are, by and large, small-scale. Ahmed et al. [31], investigated the impact of shadowing, frequency fading, and reflection on the quality of ground-to-ground, ground-to-air and air-to-ground links. Their experiments involve wireless sensor nodes carried by hexacopters flying at different heights and distances from a ground node. The experiment results revealed that the factors influenced the quality of the links considerably and the effect was further exacerbated by antenna orientations and the flying quality of the UAVs.

Huiru et al. [32] employed a pair of IEEE 802.15.4 complaint radios (CC2530 [33]) to study the quality of aerial links. One of the nodes was deployed on a UAV while the other was placed on the ground. The experiment results suggest that within the communication range of approximately $150\,\mathrm{m}$, a packet success rate of up to 80% could be achieved. Similarly, Chen et al. [34] observed that for a similar radio specification the best 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.

Nekrasov et al. [35] deployed four IEEE 802.15.4 compliant transmitters on the ground in a linear topology. Two additional nodes (receivers) were attached to a quad-copter, one of them having a horizontal antenna orientation whereas the other having a vertical orientation, thus, combined, the two antennae forming orthogonal orientations. The experiment results suggest that the link quality in terms of RSSI was almost the same for both antenna settings (less than 1 dB difference by mean values). However, the packet success rates were affected dramatically by the orientation. When the UAV flew at $76\,\mathrm{m}$ height and $100\,\mathrm{m}$ horizontal distance away from the transmitters, the packet success rate of the horizontal setting was above $75\,\%$ while it dropped less than $25\,\%$ for the case of the vertical orientation. In order to achieve a better communication performance, the authors suggest that the transmitter deployment, the altitude of the UAV, and the antenna orientation of the receiver should be optimized.

The above studies focused on investigating the characteristics of low-power wireless links established between UAVs and ground sensor nodes and how they are affected. One can characterise these studies as initial stages in link quality characterisation. The next logical step is to develop theoretical models based on the experimental observations, so that predictions can be made pertaining to link quality fluctuation, which is vital to plan the scope and duration of a deployment. To the best of our knowledge, ours is the first proposal to model link quality fluctuation as a Poisson stochastic process. We demonstrated how the model can be used to estimate goodput and short-term link quality stability.

VI. CONCLUSION

In this paper we conducted several experiments to investigate and characterise the aerial links established between wireless sensor networks on the ground and unmanned aerial vehicles when they are jointly used to monitor inaccessible, dangerous, or extensive outdoor environments. The IEEE 802.15.4 specification provides 16 channels, each having a bandwidth of $2\,\mathrm{MHz}$ and separated from neighbour channels by a $5\,\mathrm{MHz}$ guard band. The wireless sensor network and the unmanned aerial vehicles operate in the same ISM band, even though they may occupy different channels at any given time.

This results in a strong cross technology interference which affects the wireless links established between the two systems.

We investigated the binary sequence during a burst transmission, 0 signifying a packet loss and 1 signifying successful reception. Examination of the statistical properties of these sequences for different channels and wireless links suggests that link quality fluctuation can be described by a Poisson stochastic process (as a function of time). The usefulness of this model is manifold: Including the estimation of goodput, the flight time of the UAVs, and the short-term link stability. One of the essential features of a Poisson process is the rate of the process – λt. For the short-term link quality fluctuation, the rates are: λpt (signifying a good link) and λqt (signifying a bad link). Interestingly, these parameters also sufficient to describe the states expected values and variances, thus simplifying the estimation process.

The Poisson process enables to characterize link quality with any degree of confidence. However, it involves factorization, as can be seen in Equations 9, 17, and 18. For large ks, the computation is rather onerous and, in some cases, even intractable. In order to simplify this task, one may transform the expression to their logarithmic expressions. These and other aspects will be the subject of our future investigations.

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