Utilizing Link Characterization for Improving the Performance of Aerial Wireless Sensor Networks

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***Abstract*—Characterization of communication links in Aerial Wireless Sensor Networks (AWSN) is of paramount importance for achieving acceptable network performance. Protocols based on an arbitrary link performance threshold may exhibit inconsistent behavior due to link behavior not considered during the design stage. It is thus necessary to account for factors that affect the link performance in real deployments. This paper details observations from an extensive set of experiments designed to characterize the behavior of communication links in AWSN. We employ the widely used TelosB sensor platform for these experiments. The experimental results highlight the fact that apart from the usual outdoor environmental factors affecting the link performance, two major contributors to the link degradation in AWSN are the antenna orientation, and the multi-path fading effect due to ground reflections.**

Based on these observations, we propose a Link Aware Protocol for AWSN (LAAWN) that takes into account the effect of these potential sources of performance degradation. This paper details the design and performance evaluation of our proposed LAAWN protocol. We evaluated the LAAWN protocol in two real-world use cases namely delay-tolerant and real-time AWSN. The simulation results show that on average, LAAWN improves the overall network performance by reducing the percentage of dropped packets from about 34% to less than 4% for an AWSN that requires real-time data transfer.

***Index Terms*—Aerial sensor networks, link characterization, experiments, performance evaluation.**

I. Introduction

Recent advances in embedded systems and robotics have enabled a new class of mobile sensor networks, which can significantly enhance the spatial coverage of the target region. Two main advantages of mobile sensors are that they can: (i) control the deployment, thus providing optimal coverage of the desired region and (ii) dynamically repair the network, thus eliminating transmission bottlenecks and effectively increasing the network efficiency. In recent years, mobile sensors have been successfully adopted for terrestrial [1] and ocean [2] monitoring. The next logical step in their evolution is to enable mobile sensors to explore the aerial dimension, i.e., design an airborne sensor network. The objective is to amalgamate the sensing and communicating capabilities of wireless sensor networks with the autonomous flying ability of micro aerial vehicles to engineer a novel paradigm, Multi-hop Aerial Wireless Sensor Network (AWSN), wherein these small aerial vehicles equipped with wireless radio and sensors sample the physical space in three dimensions and relay the data over the underlying multi-hop wireless network to ground stations. The ground stations may then forward the information to end users via the Internet. Aerial nodes can also complement ground-deployed sensors by providing unique three-dimensional vantage that would otherwise be infeasible. The low-cost fine-grain sensing capabilities of AWSN thus enables a variety of innovative applications spanning both the public and commercial domains: tracking bushfires, sensing toxic plume behavior, and disaster reconnaissance and recovery, for example.

The sensed data from the AWSN is relayed to a ground station by equipping the Unmanned Aerial Vehicles (UAV) with a 802.11 or ZigBee transmitter. Given that wireless technologies such as 802.11 and ZigBee have a limited range, UAVs create a multi-hop aerial network such that the sensed information can be relayed back to a distant terrestrial base station. Network protocols are responsible for overseeing this data relay. In designing robust protocols, it is important to make realistic assumptions about the characteristics of the underlying communication links. This is particularly crucial in a dynamic aerial environment, since wireless communication can be affected by several factors such as interference, path loss, multi-path propagation and Doppler effect etc. [3]. It is therefore, necessary to derive realistic abstractions of the wireless communication properties for multi-hop AWSN. Recent research in AWSN has focused on distributed coordination for a swarm of UAVs [4], [5], coverage evaluation in 3D [6] etc. but not much work has been done on understanding the network connectivity dynamics for an AWSN.

A general consensus among the wireless research community is that simulation results alone do not adequately reflect the real behavior of wireless ad-hoc networks due to the simplified radio propagation models [7], [8], [3]. Protocols designed based solely on simulation studies do not always work when they are subjected to real deployments. This motivates the study of empirical link characterization in order to design robust and practical protocols for AWSN.

We make the following specific contributions in this work:

- We empirically study the link behavior for better understanding of the wireless communication characteristics between nodes in an AWSN. Communication in AWSN takes place over 3 distinct kinds of links - (i) Ground-to-Air (G-A) typically used by base stations on the ground to relay configuration commands to UAVs (ii) Air-to-Air

Manuscript received July 31, 2011; revised April 30, 2012. This article was originally assigned to the June 2012 Communications Challenges and Dynamics for Unmanned Autonomous Vehicles issue of IEEE Journal on Selected Areas in Communications. This research was supported under the Australian Research Council's *Discovery Projects* funding scheme (Grant No DP110104344).

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Digital Object Identifier 10.1109/JSAC.2013.130825.

(A-A) used for inter UAV communication for forwarding data and movement coordination and (iii) Air-to-Ground (A-G) which are used for relaying sensor data from the UAVs to the base station. Intuitively, we expect that the performance of these three kinds of communication links in an AWSN would be different based on the transmitter-receiver antenna heights above ground and ground reflections etc. We characterize each type of link, both in isolation and in a multi-hop scenario, to evaluate the differences in their expected performance.

- We observe factors most critical for the design of robust network protocols in AWSN and make design recommendations that are generally applicable for any ZigBee based AWSN. The experimental results from a systematic set of link characterization experiments indicate that TelosB antennas have directional bias where the radiated signal strength varies in different directions. We also observed that fading effect due to ground reflections creates grey areas of communications where the link performance degrades considerably.
- Based on the observations from the link characterization experiments, we design and evaluate LAAWN, a topology control/link quality enhancement protocol, to improve the network performance of an AWSN. Nodes participating in the protocol are link aware i.e., they can overcome the adverse link conditions by re-orientation of their antennas and a change in the height/distance combination to alleviate the multi-path fading effect.
- We perform a simulation study to evaluate the performance of our proposed LAAWN protocol using two realistic use cases of airborne networks namely delay-tolerant and real-time AWSN. Performance evaluation results show that the LAAWN protocol considerably improves the overall performance by reducing the number of dropped packets for both the delay-tolerant and real-time use cases of AWSN.

Note that we have used static plastic poles for 3D placement of nodes for these link characterization experiments. The use of poles limits the height of the sender/receivers (4.2m is the maximum height used in the experiments) but gives more control over the test environment in conducting and repeating the topology for experiments. However, this static placement of the nodes does not capture the effect of UAV movements (e.g., the Doppler effect) on the link characteristics. We do not expect Doppler effect to be severe at the mobility speed of a few km/h typical for these hovering UAVs. The presented results are also specific to the TelosB WSN platform that we have utilized for our work. The antenna characteristics would be different for a WSN platform employing different antennas. We believe that the design recommendations from this study are still generally applicable for any low-powered ZigBee based AWSN.

The rest of this paper is organized as follows. Section II discusses the related work. Results from the link characterization experiments are detailed in Section III. Section IV details the protocol design for the LAAWN protocol while the simulation study to evaluate the performance of the LAAWN protocol is described in Section V. Conclusion and future work is discussed in Section VI.

II. Related Work

In this section, we present a brief overview of previous work covering the link characterization in wireless sensor networks and application of link quality metrics for optimizing links in a wireless network.

There is a vast body of research work available in literature covering the link characterization for terrestrial WSN [7], [9], [10], [11] and [12] etc. These research studies found that low-power wireless links in WSN are susceptible to spatial as well as temporal variability. Authors in [7] proved that radio connectivity is not a simple disk while [10] and [11] showed the presence of "grey area" in wireless communications with high variance in packet reception rates. Zuniga et.al. in [12] described three distinct reception regions in a wireless link: connected, transitional, and disconnected. The transitional region has highly unreliable links and its region bounds can be found either by analytical or empirical methods [12] [3]. Our experimental study also confirmed the presence of grey zone of communications for 3D wireless sensor networks.

Studies covering link characterization for 3D wireless networks reported in the literature are based on different types of communication link technologies - (i) WiFi links [13], [14] (ii) a combination of WiFi and cellular communications [15], [16] (iii) ZigBee based links [17], [18], [19]. Authors in [17] showed that antenna orientation is a dominant factor affecting the Received Signal Strength Indication (RSSI) sensitivity especially for 3D scenarios. Their empirical study was based on ZigBee based network using mono-pole antennas. Allred et.al. in [18] presented results from their ZigBee based wireless characterization experiments using XBee Pro mounted SensorFlock platform. The quarter wave whip antenna used in their experiments also showed orientation bias performing best when the angle between the vertical transmit antenna and the receiver UAV was close to 90 degrees. Teh et.al. [19] used the Fleck3 platform mounted on a fixed wing airborne vehicle to perform communication range testing. They employed an external antenna with the Fleck operating at 900 MHz band. For our link characterization experiments, we employ widely used off-the-shelf TelosB WSN hardware platform [20], that has a PCB mounted inverted F antenna [21]. The use of off-the-shelf WSN devices permits easy integration with the UAV platform resulting in rapid design and deployment.

Estimation of the quality of wireless links is vital for optimizing protocols in wireless sensor networks. Srinivasan et.al. [23] showed that RSSI is a useful link quality indicator. He et.al. in [24] used RSSI to predict link quality for topology control through local optimization of nodes transmission power levels. We used RSSI in combination with packet reception rates as metrics to classify links in our characterization experiments. Topology control based on link quality for 3D WSN is usually accomplished by varying the transmission power levels of individual nodes [25], [26]. In our work, we assume that all nodes have fixed transmission power and utilize mobility of UAVs to improve the link quality for individual links in the topology.

III. Link Characterization Experiments

We conducted three sets of experiments employing the TelosB platform. The first set of experiments, referred as

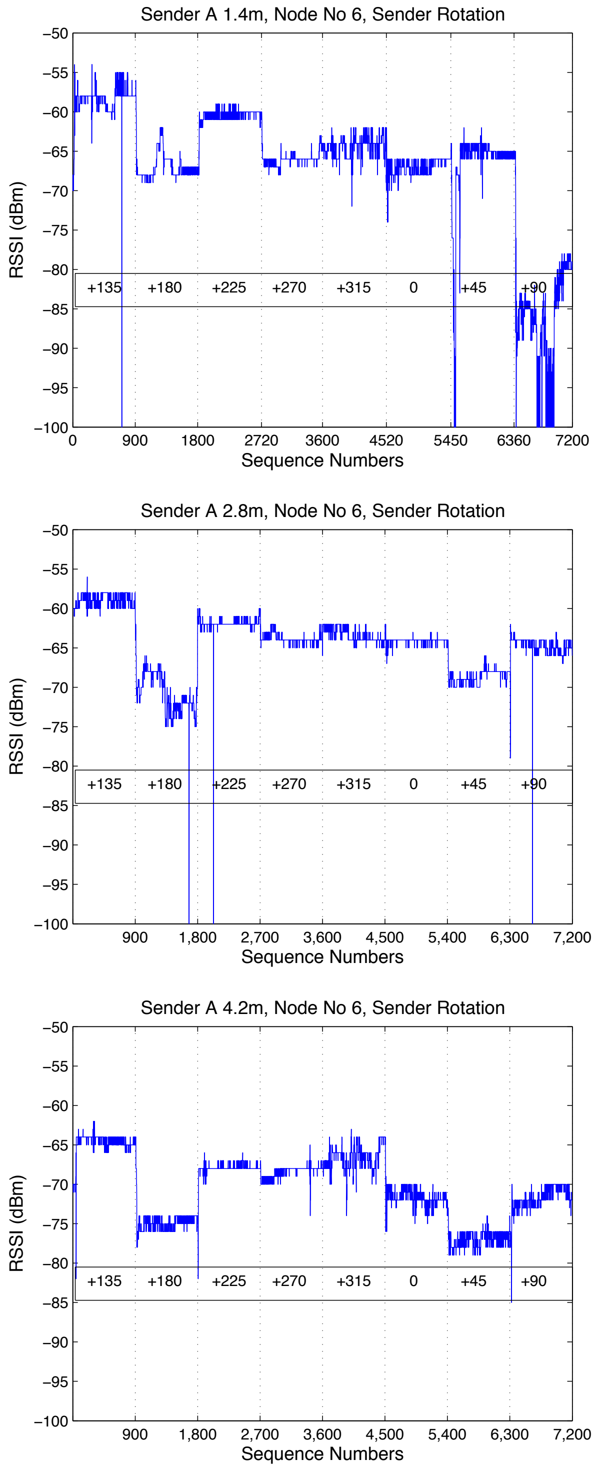

Fig. 1. RSSI values with Sender Rotation for Varying Heights

the antenna orientation experiments, aims to quantify the performance of the TelosB platform with respect to the node mounting position and the sender-receiver antenna orientation. The antenna on-board the TelosB is a standard inverted F type antenna and its typical radiation pattern is not truly omni-directional [21]. The mounting position of the WSN node on the UAV would thus affect the signal radiation in different directions. The second set of experiments evaluate three different kind of communications links namely G-A, A-A and A-G with respect to varying distances and heights above ground. This set is called the single-hop experiment. The last set of experiments, called the multi-hop experiment, evaluates the performance of the three different kinds of communications links simultaneously. This experiment captures the effect of inter-link interference in a multi-hop environment. Some of the preliminary results appeared in a workshop paper [22].

All of these experiments were conducted outdoors in a parkland (Centennial Parklands, Sydney). In order to measure the external interference caused by WiFi operating on the same 2.4 GHz frequency band, we first conducted a radio frequency spectrum survey using a spectrum analyzer and found only a single wireless access point occasionally active on WiFi channel 6. All WSN nodes were tuned to operate on ZigBee channel 26 known to be immune from the external interference. The floor noise level measured by the TelosB nodes vary between -90 to -93 dBm.

We performed system calibration of the TelosB nodes to measure the node-to-node differences in the receiver sensitivities. We mounted SMA receptacle jacks on TelosB nodes (disabling the PCB inverted F antenna) and connected each node to a sender of known signal power through a coaxial cable. This wired setup enabled us to measure each receiver response to a signal of known power from the sender. We observed that six of the eight tested TelosB exhibit similar receiver behavior and that response from only two nodes differ by +/- 2dB from the rest of the tested nodes (details excluded for brevity). This calibration data was used to adjust the actual data collected in the characterization experiments.

A. Antenna Orientation Experiments

In order to evaluate the directional bias and the radiation pattern for the TelosB nodes, we employed a nine TelosB nodes star topology for this experiment. One node configured as the sender was placed at the center and programmed to send broadcast packets at the rate of 300 packets per minute (inter packet interval of 200 msec). Receivers were placed at 4cm above ground on inverted foam glasses, arranged at 45 degree angles at a distance of 10m from the center with their antenna facing towards the center (For details refer to our technical report [27]). Receivers logged the sequence numbers and RSSI values of received packets in their flash. We varied the height of the sender node mounted horizontally on a plastic pole for different run of the experiments. Sender rotation was achieved by changing the direction of the sender 45 degrees after every three minutes. The experiment was then repeated with three different sender nodes to avoid any possible hardware bias. The transmission power for all the nodes was set at 0 dBm (maximum power). In order to eliminate the effect of battery voltage on node's transmission power, we ensured that minimum individual battery level was above 1.4V for all the experiments.

Figure 1 shows the result of sender antenna rotation experiment for one of the receiver node (Node No 6) with the sender height varied between 1.4m to 4.2m above ground. Zero degree rotation means that the sender and receiver antenna are directly facing each other. Results show that antenna orientation affects the RSSI values at the receiving nodes. We

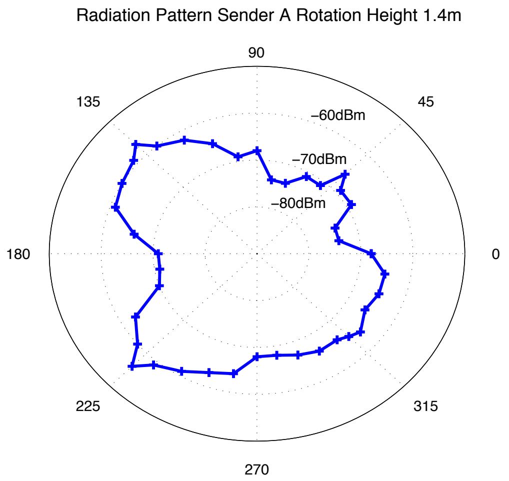

Fig. 2. Radiation Pattern for a TelosB Sender

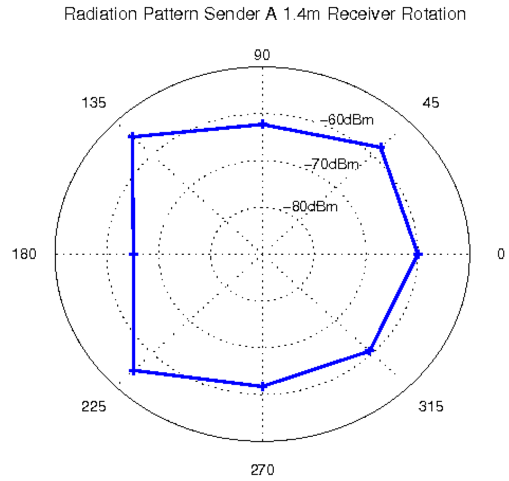

Fig. 3. Radiation Pattern for Receiver Rotation

observed that on average RSSI values vary atleast 10dB for the best and worst antenna orientation for all height variations. This observation is consistent for all the receivers, for all height variations for the three different senders.

We next conducted another experiment, where eight receivers were placed at 10 degree orientation around the sender and the sender was rotated by 45 degrees to cover the full 360 degrees rotation, in order to plot the fine-grained radiation pattern for the TelosB nodes. The radiation pattern observed is shown in Figure 2, where average RSSI values across all the receiver nodes have been plotted. The results show the existence of regions of better RSSI reception at around 135 and 225 degree orientation. This confirms that the radiation pattern is not truly omni-directional and that the RSSI values depend on the relative direction of the receiver in the sender's antenna radiation pattern.

Note that the RSSI values are affected by a variety of factors beside the antenna orientation. In order to isolate the experimental results from the effect of fading and multi-path, we conducted an experiment in a RF anechoic chamber to plot nodes' free-space antenna patterns. Both sender and the receivers were placed about 1m above the ground. RSSI values at receivers were also confirmed by a co-located spectrum analyzer for the sender rotation in the anechoic chamber. The radiation pattern observed in the anechoic chamber (for details, refer to our technical report [27]) confirms the dependence of RSSI on antenna orientation similar to the one observed in the outdoor experiments.

We also conducted a variation of the sender rotation experiment where the sender is vertically mounted (with the antenna pointing towards the ground) on the plastic pipe and rotated along the vertical axis while the receivers were still horizontally mounted on the foam glasses. Results showed that horizontal mounting results in much better RSSI values than the vertical mounting implying that AWN nodes should have horizontally mounted TelosB nodes for improved performance.

We next conducted another set of experiments to confirm the reciprocity theorem, that the antenna's receiving pattern also performs at its best in the same preferred directions identified in the sender's radiation pattern. We conducted experiments with different sender antenna orientation with the same star topology but with 45 degree receiver rotation taking place after every minute. The sender is also rotated by 45 degrees after every eight minutes.

Results in Figure 3 show that RSSI values increases by about 6dB when the receiver antenna is oriented at either 135 or 225 degrees with respect to the constant sender orientation. The experiment was repeated for different constant sender orientations with best results obtained when both sender's and receiver's preferred regions of RSSI overlap each other.

In summary, following are the key findings from the first set of experiments:

1) The TelosB devices exhibit directional bias in the observed radiation pattern with two distinct regions of better RSSI reception. This observation is useful for an aerial network where the UAV can rotate and orient itself to achieve better network performance.
2) Horizontal mounting of the TelosB nodes on the UAV results in improved RSSI values as compared with the vertical mounting.

B. Single-Hop Experiments

The objective of this experiment was to analyze the behavior of three different types of communication links that is G-A, A-A and A-G. We conducted these experiments with two TelosB motes communicating with each other. The sender node sends 300 data packets per minute to the receiver node, and the receiver replies back to the sender. Both nodes log the RSSI and sequence numbers of each received packet. We measured the RSSI and Packet Reception Rate (PRR) for different sender/receiver height combinations (0.04m, 1.4m, 2.8m and 4.2m) and by increasing the distance between the nodes in increment of 10m until the PRR dropped below 20%. Antenna orientation for both sender and receiver was kept constant (parallel to each other and pointing in the same direction) for all run of these experiments.

Figure 4 shows the results for G-A case when the sender is placed at about 4cm above ground for varying heights of the

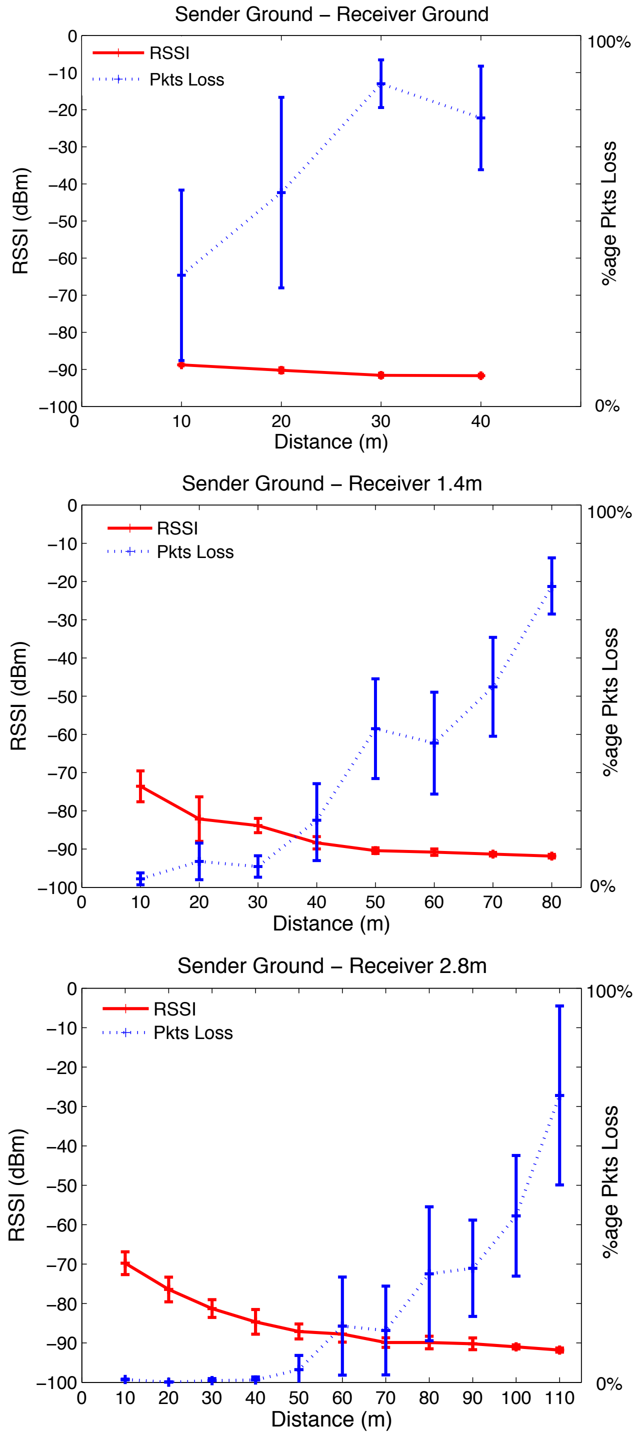

Fig. 4. RSSI and Packet Loss Values for Ground to Air Communications

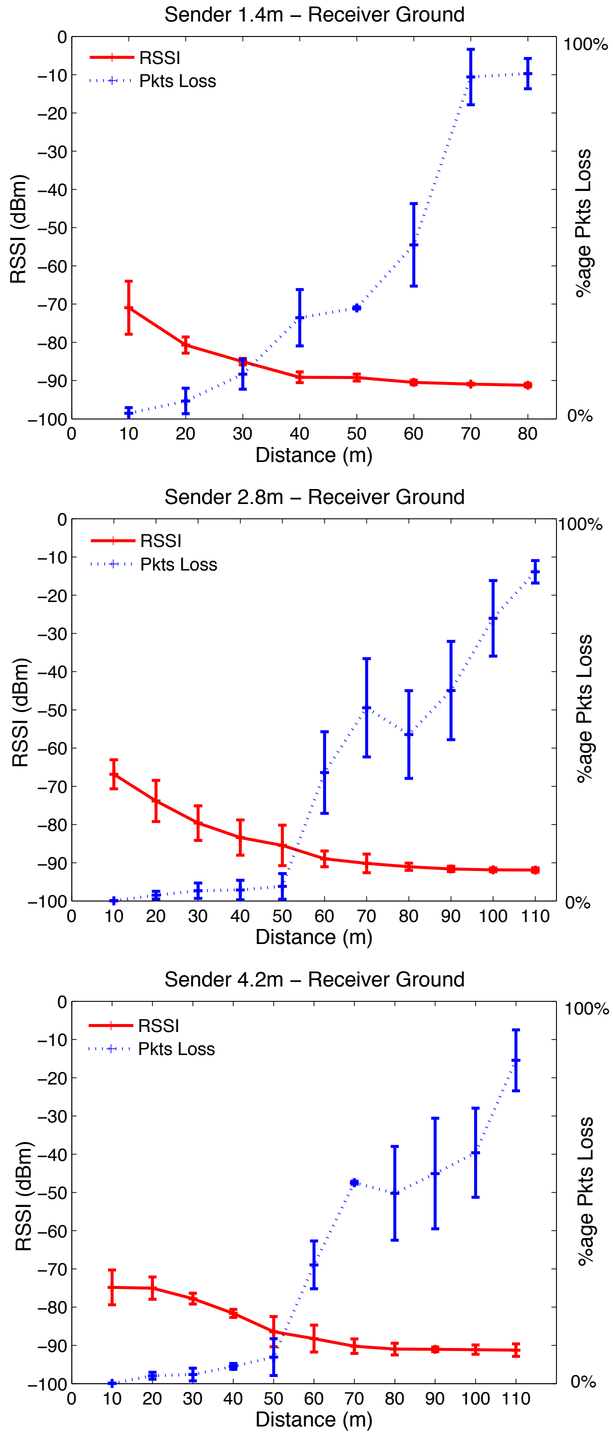

Fig. 5. RSSI and Packet Loss Values for Air to Ground Communications

receiver. We observed that the RSSI and PRR improves when the height of the receiver is increased. Worst performance is achieved when both sender and receiver are close to the ground. Raising the receiver about 1.4m and 2.8m above ground results in successful PRR of greater than 80% for distances up to 40m and 70m respectively. The reason for performance improvement can be attributed to the effect of ground (reflections, absorptions etc) being reduced when the receiver is raised above the ground.

Figure 5 shows the results for A-G links when the height of the sender is increased from 1.4m to 2.8m and 4.2m above ground while the receiver is placed about 4cm above ground. We observed that generally successful packet reception rate improves with increase in height of the sender due to reduced effect of ground. Comparing the results for G-A and A-G communications in Figures 4 and 5, we found that G-A communications links perform relatively better than the A-G links where better packet reception rates are obtained at longer distances. Several factors can contribute to this difference in performance between A-G and G-A links. For example, change in location of receiver in the sender's antenna radiation pattern for A-G and G-A communications (Section

No III-A), shadowing effect caused by blocking of line-of-sight by node's/UAV hardware [14] and variation in the ground reflections.

We next conducted experiments to evaluate the performance of A-A communications links. Results are shown in Figure 6 where the expected path-loss given by Friis free space model and Two Ray Ground approximation model are also plotted. We note that as compared to the G-A and A-G scenarios, much better packet reception rates are obtained when both the sender and the receiver are at a height above the ground. Figure 6 shows that greater than 80% of successful packet reception rate is achieved up to a distance of 130m between the sender and receiver when both are at a height of 1.4m above the ground. The distance increases to about 220-240m when the sender is at 1.4m height and the receiver height is either 2.8m or 4.2m. We also observed the presence of grey regions of communication, where the PRR falls considerably before improving again when the receiver moves further away from the sender. The relative packet loss within these grey zones increases by 30% to 60% as shown in Figure 6. The location of these grey zones depends on the height of both sender and the receiver e.g., for sender at 1.4m and receiver at 2.8m, it occurs at a distance around 80m from the sender.

1) Discussion: For better understanding of the grey regions, we re-visit the Friis free space and the Two Ray Ground approximation propagation models [28]. The free space model assumes no signal absorption or reflection in the environment. The transmit antenna is modelled as a point source with propagated energy spread over the surface of a spherical wavefront. If P_t is the transmit power, the power received P_r at a distance d is inversely proportional to the sphere surface area $4\pi d^2$ and is given by

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \quad (1)$$

where λ is the wavelength (speed of light divided by the carrier frequency) and G_t and G_r are the transmit and receive antenna gains respectively.

The terrestrial propagation environment is not free space. If H_t represent the height of the sender antenna above ground and H_r the height for the receiver, then the difference in length of the line of sight path (L_{los}) between the sender and receiver and the length of the ground reflected wave (L_{grw}) results in a phase difference or shift between the two received waves given by

$$\varphi = \frac{(L_{grw} - L_{los})2\pi}{\lambda} \quad (2)$$

We can thus calculate the distance between the sender and receiver, given the carrier frequency and the height of the sender and receiver, at which the phase shift is exactly π. At this distance the line of sight wave and the ground reflected wave tend to cancel each other out resulting in areas of poor reception as experienced in the field measurements. The Two Ray Ground approximation is given by

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \left[\frac{4\pi H_t H_r}{\lambda d} \right]^2 \quad (3)$$

Depending on the phase difference between the arriving signals, the interference can be either constructive or destructive, causing a very large observed difference in the amplitude of the received signal over very short distances. In our test environment, there were no obstructions nearby. So fading is predominantly caused by ground reflections causing destructive interference to the original signal due to the multi-path fading effect. Comparing the expected path-loss given by Friis model (free space) and Two Ray Ground model in Figure 6, we can observe that the presence of grey zones coinciding with the points where Two Ray Ground model indicates presence of destructive interference. Note that the RSSI (and the packets loss) has been observed at discrete distances, in steps of 10m, which often does not exactly coincide with the continuous crest/troughs given by the theoretical Two Ray ground model approximation. Also note that the observed RSSI values are always lower than that given by the approximation models. This difference can be attributed to the assumptions made in the approximation model regarding the isotropic antenna behavior (we have already observed directional bias in Section III-A) and ground reflection coefficient that affects the phase shift characteristics.

In summary, the experiments discussed in this section have highlighted the following important observations:

1) The Air-to-Air communications links perform the best among all types of links for the single-hop experiments.
2) The Ground-to-Air link performs better (higher PRR at longer distances) than the Air-to-Ground link when the ground nodes are placed at 4cm above ground.
3) The PRR improves considerably when the sender/receiver are placed above the ground compared to the case when placed on the ground. This suggests that the base station should be placed at a height above the ground to achieve better PRR.
4) Grey zones, present when both the sender and receiver are placed at a height above the ground, can cause the relative packet loss to increase by 30% to 60%. This information is vital for resilient design of protocols in aerial WSN. The protocol designer must be aware of the presence of the grey zones due to fading and must incorporate remedial measure to alleviate the effect of such grey zones.

C. Multi-Hop Experiments

In the previous section, we measured the performance for three different kinds of links separately. We next conducted multi-hop experiments where all three types of links were used simultaneously. The objective was to measure the overall network performance in the presence of inter-link interference and to identify the bottleneck link for a multi-hop AWN.

Four nodes are placed in a line topology with a similar inter-node distance. We changed the inter-node distance to 10m, 20m, 30m and 40m for different runs of the experiment. A sender node (*S*) sends 1800 packets at the rate of 300 packets per minute addressed to the receiver node (*R*) which replies back with Acks. All communication between *S* and *R* takes place over multi-hop links using two relay nodes nodes in the topology. *S* and *R* are placed 4cm above ground while the height for the relay nodes is varied for different run of

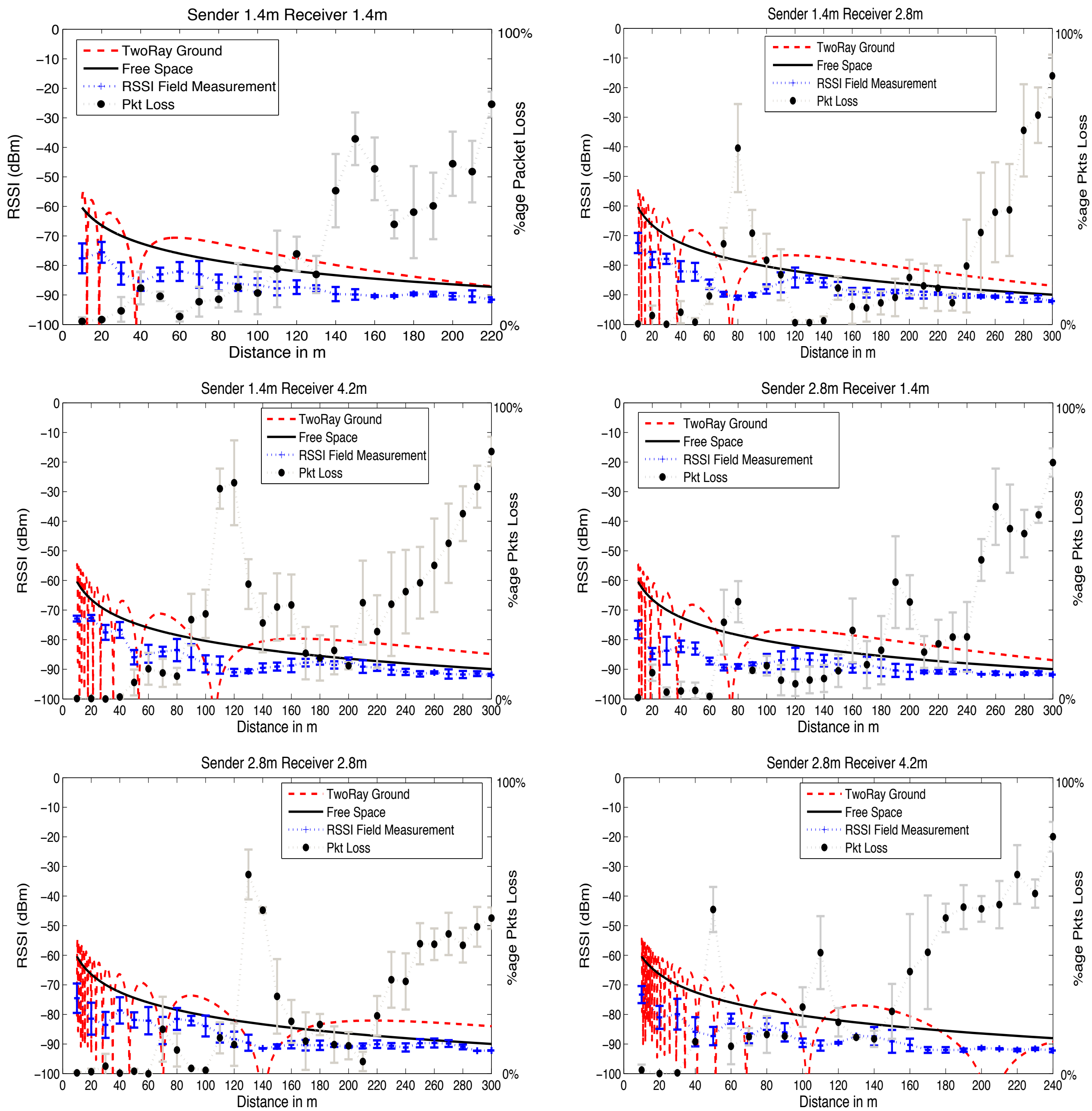

Fig. 6. RSSI and Packet Loss Values for Air to Air Communication

the experiment. All experiments were run with fixed antenna orientation for all the nodes.

Figure 7 shows the overall PRR as well as the performance of different links for the multi-hop setup. The End-to-End PRR involves six communications links, two of each type A-G, A-A, and G-A in forward (S towards R) and backward (R towards S) directions. We can observe that for a fixed height of the two relay nodes, as expected, the End-to-End PRR deteriorates with the increase in the distance between the nodes. The individual A-A links performed the best in multi-hop experiments while the A-G shows the worst performance. For the two A-G links in the topology, the average PRR drops to about 71% when the inter-node distance is increased to 40m for 1.4m height of the relay nodes. These results are consistent with the results from the single-hop experiments. Comparing the results for 1.4m and 2.8m heights for the relay nodes, the End-to-End PRR for 40m inter-node distance improves from about 23% to about 48% when the relay nodes are raised from 1.4m to 2.8m above ground.

IV. Protocol Design

Based on the recommendations from the link characterization experiments discussed in the previous section, we have designed the LAAWN protocol. The objective is to enhance the link quality between the nodes in an AWSN by taking advantage of the observed empirical link characteristics. There are two important design considerations. First is the antenna orientation awareness (Section II.A characteristic No 1). We assume that the UAVs are equipped with GPS and compass enabling localization in 3D. Each UAV exchanges

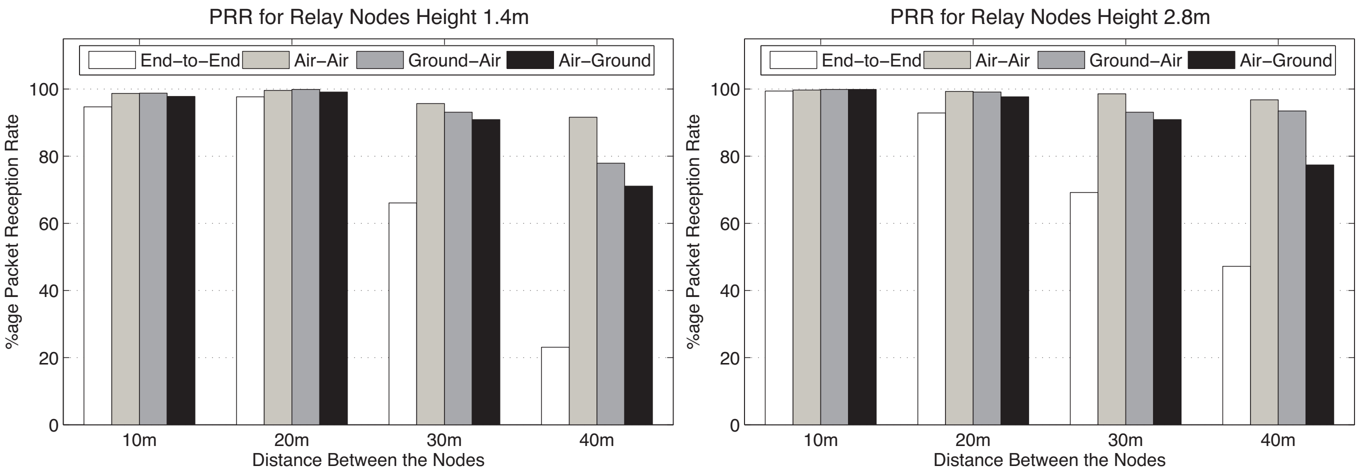

Fig. 7. Packet Loss Values For Different Links

Algorithm 1 LAAWN Protocol

Notations :
N_j = Set of neighbors,
θ = antenna orientation
INIT :
Base station broadcast HELLO message
if HELLO message received from Base Station **then**
  Evaluate θ to base station and re-orientate if required
  Store NodeId, 3D Location in N_j
Process :
if a valid route to Base station exists **then**
  Broadcast own Hello Message
if Hello message received from a Node **then**
  Store NodeId, 3D Location in N_j
  Sort N_j based on HopCount
  Check θ to node with lowest HopCount, re-orientate if required
if Data to send **then**
  Evaluate grey zone using Equation No 3
  if Can buffer **then**
    while In grey zone **do**
      Suspend Data transmission
  Change position
  Send updated Hello message

this information with its neighbors and thus knows its antenna orientation w.r.t. its communicating neighbors. We also assume that the antenna orientation can be changed dynamically through simple UAV rotation (consistent with the current capabilities of non-fixed wing UAVs). Second consideration is how to avoid the grey regions caused by the fading effect due to ground reflections (Section II.B characteristic No 4).

We now describe the details of the LAAWN protocol (Algorithm 1). We assume that the base station has a fixed antenna orientation. The protocol starts with the advertisement of Hello messages from the base station that contains the 3D (x,y,z) coordinates and its antenna orientation w.r.t. a common axis (can be taken as Magnetic North from the compass). Each node on reception of this Hello message, marks the base station as its one hop neighbor and evaluates its current antenna orientation w.r.t. the base station's antenna orientation. If required, the node immediately re-orientates its antenna such that it is making an angle of either 135 or 225 degrees to the base station antenna. The node now starts periodic advertisement its own Hello messages. The Hello message from the nodes contains the 3D (x,y,z) coordinates of the sender, its current antenna orientation, the next-Hop node, and the HopCount cost to the base station.

Nodes build their neighbor table on reception of Hello messages. The neighbors are prioritized based on the hop-count values in the advertisement, the node with the lowest hop-count selected as the next-hop node. Each node re-orientates its antenna to the preferred orientation of either 135 or 225 degrees w.r.t. the selected next-hop node, before advertising its own Hello messages.

For nodes that are static (e.g., fixed position relay nodes in an AWN), the content of the subsequent Hello messages would not change. For aerial nodes that are constantly in motion, the link to the next-Hop node and the required antenna orientation may change with change in its position. A node only re-orientates if the required change in antenna orientation is more than 20 degrees, instead of constantly changing the antenna orientation with the movement. Any change in the neighbor table (discovery of new neighbor, change in upstream link, re-orientation of the antenna etc.) immediately triggers a broadcast of new updated Hello message. Each entry in the neighbor table also has an associated KeepAlive timer that is used to check the validity of the advertised link. Once the neighbor tables are in place, a node that wants to transfer data to the base station checks the validity of the next-hop link before starting the data transfer.

To counter the fading effect, a sender node utilizes Two Ray Ground approximation model (Equation No 3) to evaluate whether transmissions from its current location to a receiver would be affected by the multi-path fading due to ground reflections or not. If a mobile node with buffering capabilities finds that the current position is not suitable for transmission (inside a grey zone), it can simply suspend its current transmission and wait for the improvement of the link conditions due to its constantly changing position. Static relay nodes can also dynamically adjust their position in the topology to achieve better link performance.

Nodes participating in the LAAWN protocols can thus take remedial measures to overcome the adverse effect of multi-path fading and can re-orientate to further improve the link performance.

V. Performance Evaluation

We consider two real-world use-cases of Aerial Networks for performance comparison of our LAAWN protocol. First use-case is the Delay Tolerant Aerial Network (DTAN). In DTAN, multiple UAVs with buffering/storage capabilities traverse different parts of the target area collecting and storing sensed samples. These UAVs transfer their stored samples once they come in communication range of a static base station during their journey. Example of a DTAN could be an aerial network tasked with sensing the air quality/pollution in a given target area. Second use-case of aerial network is the Real Time Monitoring Aerial Network (RTMAN), where all the sensed information is transferred to the static base station in real time through multi-hop. These type of aerial networks may be required in a real time search and rescue operation, a surveillance mission or for toxic flume measurement.

The current implementation of the Ns-2 network simulator [29] lacks the support for 3D aerial networks. Based on the results from our link characterization experiments, we derived the statistical properties for an empirical propagation model that incorporates both the antenna orientation and two-ray ground reflection model. We modified the wireless-physical layer of Ns-2 to add this aerial propagation model. We also introduced random variation in the propagation losses, bounded by the errors observed in the link characterization experiments, such that the links vary stochastically over the period of simulation.

We setup the DTAN and the RTMAN aerial network topologies in Ns-2 for running the simulations with four different protocols, Default(protocol where the UAVs are not aware of orientation and multi-path fading effects) and three variants of the LAAWN protocol. Orientation Aware is a version of the LAAWN protocol where the UAVs can only change their antenna orientation w.r.t. the receiver to improve the link performance. In Fading Aware, the UAVs can suspend their current transmission or change their height or distance to the base station if they are in a grey region due to the multi-path fading effect. LAAWN is the full version protocol where both antenna orientation and height/distance combination can be changed by the UAV to improve the link performance. We simulate the performance of each of the above protocol to compare the improvements achieved by each enhancement in the LAAWN protocol.

A. Delay Tolerant Aerial Network

We employ 4 UAVs for this set of simulations in an area of size 1000m x 1000m. The base station is located in the center of the topology (at 500m,500m) at a height of 1.5m from the ground. The flight paths of the UAVs are shown in Figure 8. Each UAV takes three rounds of its allocated area flying at a different height (5m, 10m, and 15m from ground) in each round. The UAV samples the environment (For example, air quality measurements) at the rate of four sample per minute and logs the sequence number and the sensed value in its flash. The UAV starts data transfer as soon as it gets in the communication range of the base station. We assume that each packet can accommodate two data samples. Note that as the antenna orientation of the base station is fixed, each UAV have different antenna orientation when approaching the base station. In Orientation Aware variant, UAV can re-orientate to get better link quality but disregards the effect of fading in grey zones. For Fading aware variant, for countering the fading effect, UAV simply suspends the current data transmission and only resumes when it moves out of the grey region of communication but does not perform re-orientation. LAAWN, on the other hand, utilizes both the grey zone avoidance and re-orientation methodologies.

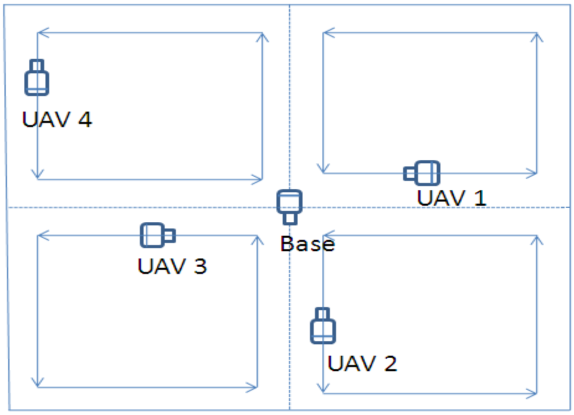

Fig. 8. Topology for the Delay Tolerant Aerial Network

Figure 9 shows the overall successful PRR as well as the individual PRR for each UAV in the DTAN with different protocols. The results are the average from five runs of simulations for three different heights of the UAVs. The results show that LAAWN improves the overall PRR from about 85% using the default protocol to approximately 99.5%. Orientation and Two Ray aware variants also improves the performance as compared to the default protocol by about 7-8%. The combination of both the antenna orientation and the multi-path fading in LAAWN performs the best in improving the network performance.

B. Real Time Monitoring Aerial Network

For the RTMAN topology, the Mobile Monitoring Aerial Unit (MMAU) consists of a master UAV flying at 10m height and two slave UAVs flying at 5m height. The slave UAVs are equipped with the sensors (such as cameras) to collect real time information from the area and can only communicate with their master UAV. The master UAV, on the other hand, is responsible for controlling the flight path of the MMAU and collection of sampled data from the slave UAVs. The Master UAV then forwards the collected data to the base station over a multi-hop network. The base station is at 1.5m height from the ground and located in the lower middle of the topology (Figure 11). UAV4 through UAV8 are the relay nodes flying at the height of 10m from the ground. We set the the inter-relay UAV distance of 20, 25 and 30m in different runs of the

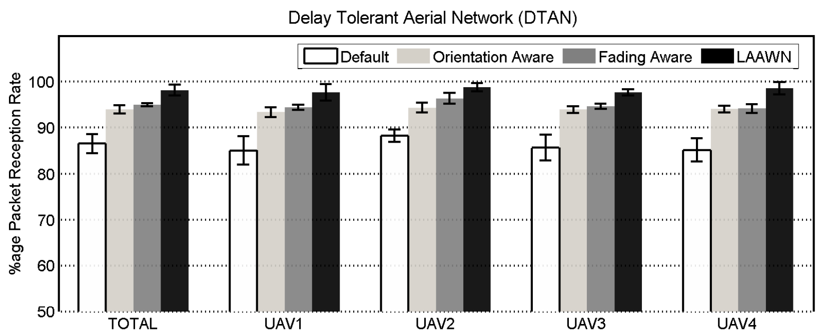

Fig. 9. Packet Reception Rates for DTAN

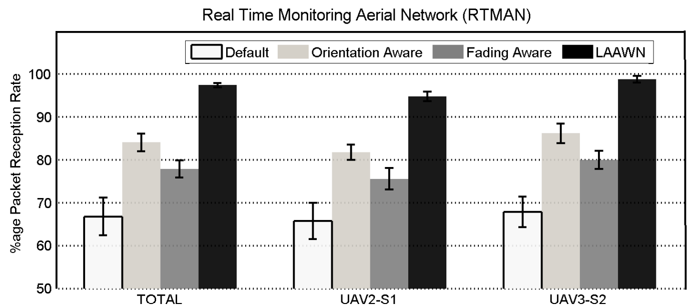

Fig. 10. Packet Reception Rates for RTMAN

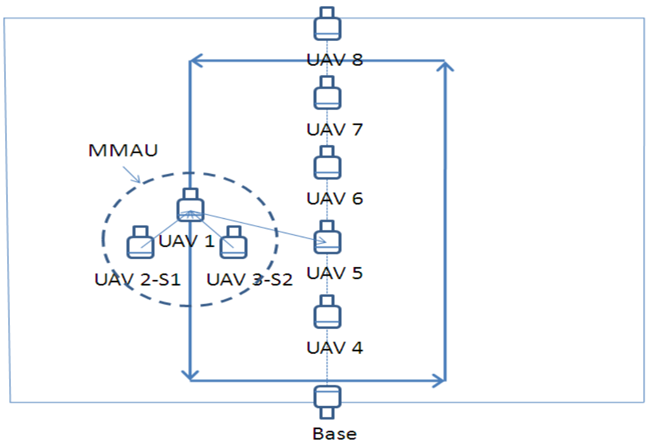

Fig. 11. Topology for the Real Time Monitoring Aerial Network

simulation. The relay nodes in RTMAN, although considered static, evaluates the grey zone fading effect and can move to adjust the inter-relay distance for link improvement. Similar to the DTAN, we conducted simulations for four different protocols to compare the performance.

Figure 10 shows the results from the simulation study. The results are the average from three inter-relay distances (20, 25 and 30m) for five different runs of the simulation. As expected, the overall PRR for the RTMAN setup is lower compared to the DTAN simulations. The reason for this performance degradation is the multi-hop nature of data transmission. A data packet in RTMAN, in the worst case, has to traverse seven links in the topology to reach the base station, increasing the probability of a packet drop. The overall PRR is improved from 66% for the default case to 79% and 83% for Fading and Orientation aware protocols respectively. The LAAWN protocol again performs the best improving the PRR to approximately 96%, an improvement of about 30%.

VI. Conclusion and Future Work

We have presented the design and performance evaluation of a link aware protocol for AWN. The design is based on recommendations from an experimental study to characterize the link performance for an AWSN. The study highlighted that for TelosB platform antenna orientation and multi-path fading due to ground reflections affects the aerial link performance considerably. LAAWN protocol alleviates the effect of these potential factors and improves the overall network performance by 14% for DTAN and close to 30% for RTMAN aerial networks.

We have observed that the TelosB PCB mounted inverted F antenna is not completely omni-directional (in 3D). As a future work, we will be investigating the use of externally mounted antennas to minimize losses and distortions in UAVs communications. Moreover, for UAVs that can keep a stable antenna orientation and travel more or less in the same plane, a single antenna might suffice, but in general a minimum of two, and probably more, antennas would be required for reliable communication in arbitrary directions between nodes of a distributed AWSN. We plan to investigate the use of dynamically switchable multiple antennas in AWSN that could be suitably arranged to cover communications in all directions. Finally, we will implement the LAAWN protocol on real hardware to quantify its performance on real deployments. We have recently acquired MikroKopter HexaKopters [30] that we will utilize for our future aerial network experiments in a real 3D environment.

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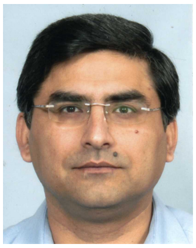

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