An approach to Integrated Spectrum Efficient Network Enhanced Telemetry (iSENET)

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Abstract

As the integrated Network Enhanced Telemetry (iNET) program moves forward in resolving systems engineering design and architecture definition, critical technology "gaps" and a migration path to realizing the integration of this technology are needed to insure a smooth transition from the current legacy point to point telemetry links to a network oriented telemetry system. Specifically, identified by the DoD aeronautical telemetry community is the need for a migration to a network solution for command, control, and transfer of test data by optimizing the physical, data link, and network layers.

In this paper, we present a networkcentric telemetry approach based on variants of 802.11 that leverages the open standards as well as the previous Advanced Range Telemetry (ARTM) work on the physical layer waveform. Specifically, we present a burst modem approach based on the recent AOFDM 802.11a work, a TDMA-like MAC layer approach based on 802.11e, and then add additional MAC layer features to allow for the multi-hop aeronautical environment using a variant of the current working standards of 802.11s. The combined benefits of the variants obtained from 802.11a, 802.11e, and 802.11s address the needs for both spectrum efficiency in the aeronautical environment and the iNET program.

Key Words: iNET, Burst Modem, TDMA, 802.11, MAC

I. Introduction

As the integrated Network Enhanced Telemetry (iNET) [1]-[3] program moves forward in resolving systems engineering design and architecture definition over the next year, ***critical technology "gaps"*** and a ***migration path to realizing the integration of this technology*** from the legacy point to point telemetry links will be essential to the success of iNET. Identified by the DoD aeronautical telemetry community is the need for a migration to a network solution for command, control, and transfer of test data by optimizing the physical, data link, and network layers. iNET will involve two time horizons, a CTEIP phase 2 development in a 3-5 year range (Block 1) and a second long term 20 year horizon architecture. This paper presents an approach to resolving the key technology gaps in the identified areas of transceivers and communications protocols in the stressed aeronautical environment and communications management that will bridge the gap between the short term 3-5 range and the long term 20 year architecture. The current iNET architecture comprises of extending the life of the current streaming telemetry needs while enhancing this with a bidirectional netcentric link focusing on a "hub and spokes" topology where the Ground Station (GS) is the hub and the netcentric links to the Test Articles (TA) depict the spokes.

As captured in the preliminary iNET technology shortfalls report, critical technology shortfalls include the ***burst modem***, ***TDMA controller***, ***TDMA link layer protocols***, and ***end-to-end applications***, where longer lead time technology shortfalls include investigations into ***communications management*** and ***mobile multi-hop ad hoc routing protocols***.

II. Preliminary iSENET architecture

The integrated Spectrum Efficiency for Network Enhanced Telemetry (iSENET) approach is to offer a layer-2 subnetwork over which iNET networked telemetry can operate. The iSENET approach provides a link layer with bi-directional capability and subnetwork error characteristics needed to support networked protocols. The iSENET subnetwork addresses test range specific needs for the burst modem, the multiple access architecture, and the multiple hops to meet Quality of Service (QoS) needs that arise from networked telemetry applications with a focus on the aeronautical links.

To allow for spectrum efficiency in an environment with multiple active TAs iSENET implements Quality of Service (QoS). The QoS approach includes Layer-2 QoS mechanisms as well as communications management that allows spectrum and timeslots to be dynamically allocated. The QoS schemes are targeted to networked telemetry applications. Although the iSENET transceiver is designed to spectrally co-exist with legacy links for traditional telemetry applications, for spectral efficiency reasons, the iSENET link layer QoS mechanisms are targeted to also allow a link layer service for traditional telemetry.

The iSENET subnetwork is designed to be able to offer good subnetwork performance characteristics – even in the presence of significant site specific interference - so as to minimize complications arising from integrating it with other networks, such as SATCOM links.

Due to increased complexities associated with effectively addressing mobility within the airborne network at Layer-3, the iSENET Layer-2 subnet is designed to handle future airborne mobility induced handovers and network reconfiguration transparently to Layer-3. This also allows for spectrum efficiency and interference minimization.

In addition to the Layer-2 airborne network capabilities, this approach offers to study additional layer-3 issues related to outlying concerns that a TA of an airborne network could move to affiliate with a different GS or that long latency satellite links might be employed as part of the all over telemetry network.

A key assumption in our approach is the use of the same spectrum on both the forward and return links such that we utilize half-duplex links. Our approach focuses on the

802.11 variants and leverages the open standards as well as the previous ARTM work on physical layer approaches. Specifically, we present a burst modem approach based on the recent AOFDM 802.11a work, a TDMA-like MAC layer approach based on 802.11e, and then add MAC layer features to allow for the multi-hop aeronautical environment using a variant of the current working standards of 802.11s. The combined benefits presented on the variants of 802.11a, 802.11e, and 802.11s address the needs of spectrum efficiency for the aeronautical environment and iNET.

2.1 Layer 1/2 concerns and approaches – The Burst Modem and TDMA

In this section, we identify an approach to address the two components that have not been tested for operation in the aeronautical RDT&E environment are the burst modem and the Time Division Mulitiple Access (TDMA) controller with its associated Quality of Service (QoS) management software.

2.1.1 Objective and Approach for the Burst Modem with TDMA-like Link Layer

The aeronautical telemetry environment has a number of impairments that make fast resynchronization difficult. These impairments include low SNR, frequency selective and flat fades, extreme doppler, radar bursts, and antenna pattern and inter-channel interference. Current work using the 802.11a standard has shown that its packet preamble structure will work in the aeronautical telemetry environment [6] if proper algorithms are in place at the receiver. Complete frequency and timing synchronization can be obtained in 1600ns at signal to noise ratios as low as 0 dB. However, this preamble requires the use of a linear amplifier.

Current waveforms such as offset QPSK waveforms do not transmit as a burst modem but rather as streamlining bits. Our focus will be on 802.11 framing structures as used in the previously flight tested Advanced OFDM (AOFDM) project and the current follow-on to upgrade to a Cyclic Delay Diversity 16-QAM OFDM System with a rate 4/5 LDPC code allowing for approximately 2.4 bits/sec/Hz, nearly twice the spectrum efficiency of the current system [7]. If in fact this waveform performs as simulated with high availability, there are tentative plans to adopt as the ARTM Tier 3 waveform. The AOFDM frame structure is identical to and adopted from the 802.11 MAC framing allowing for ease of transition to allow for burst packets in a multiple access environment. This is in fact due to the rapid acquisition and synchronization functionality on a per OFDM frame basis. Refinement of the AOFDM frame versus the IP packet size is an area for performance trades.

By exploring higher burst rates and the associated benefits bandwidth efficiency requires that some form of TDMA structure be introduced. In this manner it is possible to field multiple airborne experiments simultaneously using the same channel. One problem introduced by TDMA structures is waveform timing. The time reference would be at the ground site, and there would be differing propagation delays to each of the airborne nodes. This problem can be addressed by introducing a range estimation capability into the waveform or by leveraging GPS. Alternatively, a hybrid contention access approach can provide similar timing information as well as TDMA-like scheduling and coordination.

To achieve the full benefits of the new TDMA capability, a packet capable link layer is explored. Furthermore, one can leverage the added benefits of an asynchronous TDMA structure where one can maximize packing efficiency across the various amount of traffic from the various TAs. This allows the airborne nodes to more dynamically adapt transmission rates in addition to the constant rate synchronous frame structures. The TDMA structure may be chosen to transport link layer cells which are reassembled into packet frames by means of segmentation and reassembly (SAR), or if the TDMA slots are large enough, standard asynchronous framing might be considered, such as Ethernet (802.3), or a variant of the 802.11 PHY and MAC framing.

<u>Preliminary IP Packet Length considerations:</u>

One can consider if it is viable to utilize the AOFDM frame for IP packet delineation. Our initial investigation reveals that an AOFDM frame for the 16 QAM Rate 4/5 LDPC code contains approximately 963x4x4/5 = ~ 3081 bits. This suggests that IP packet fragmentation is needed (even for typical Ethernet MTU of 1500 bytes) over AOFDM frames. Based on 10Gig Ethernet commercial hardware, a target size to consider should be at least 9600 octets with possible considerations for a jumbogram where IPv4 and IPv6 may utilize the full 16bits of packet length which corresponds to 64kB packet sizes.

Concerns as to the 802.11 approach were with the overhead associated with scheduling of resources. Some preliminary analysis is presented for a specific example of the QoS aware 802.11e link.

2.1.2. QoS and a TDMA-like approach using 802.11e

QoS requirements for TA to GS telemetry include a) priority according to data element of sensor, or data sets – prioritized in TA; b) priority according to data sets – prioritized in TA; c) priority according to test amongst tests in a test range – prioritized in GS.

Current 802.11a/b/g MAC implementations do not provide for varying priority among the competing traffic analogous to limiting the flexibility to prioritize among competing TAs. However, 802.11e presents the new capabilities of channel access and traffic specification functional flexibility to allow for QoS. The new coordination function for channel access is referred to as the hybrid coordination function (HCF) which has two modes: enhanced distributed channel access (EDCA) which provides for a contention-based channel access function and HCF controlled channel access (HCCA) which provides for a polling approach controlled by a hybrid coordinator (HC) [802.11e_commsdesign_part_1] [802.11e_commsdesign_part_2].

We focus on the HCCA function as a TDMA-like (asynchronous TDMA) mechanism that also provides support for IntServ traffic. In a multiple access scheme with multiple TAs scheduled for access to a GS as depicted in the Figure 1 below, using HCCA, the TA of choice while acting as one of many QoS aware Station (QSTA) may be granted a transmission opportunity (TXOP) by the HCCA HC co-located with the Qos aware Access Point (QAP) which is also our GS.

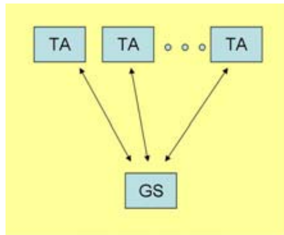

Figure 1 Multiple Test Articles with telemetry to a Ground Station

As an extension of the point coordination function (PCF) (802.11a/b/g MAC), the HCCA mechanism provides polling access to the wireless medium, but as opposed to PCF, 802.11e HCCA QoS polling can occur during contention periods (CPs) and scheduling of packets is based on admitted traffic specifications (TSPECs) as depicted in Figure 2. Of interest is the HCCA TXOP duration, the QoS CF-poll frame period, and the data transfers for QoS data frames (i.e. telemetry). Furthermore the complexity of the HCCA controller to allow for sufficient flexibility to the aeronautical environment is also a topic of interest. Key to the timing is a controlled access phase (CAP) consisting of a number of concatenated TXOPs. This concatenated set of TXOPs could correspond to a set of PCF interframe space (PIFS) times, short interframe space (SIFS) times, QoS data intervals, QoS null periods, and acknowledgements as depicted in Figure 2.

As part of 802.11e, recognize that there are up to 8 forward (downlink) and 8 reverse (uplink) traffic streams mapping to support of 8 independent backoff instances, or Traffic categories (TC). Figure 3a illustrates a ground station HCCA scheduler example using 3 TCs, assigned to “C2” (Command & Control) traffic, high priority data and regular data. In this example, the scheduler (located in the GS) is composed of strict priority (SP) selectors and fair queue (FQ) selectors. The scheduler maintains the queue states of various traffic categories of all the TAs currently under test at the test range. Based on the queue states the scheduler indicates to the HCCA scheduler how transmission opportunities (TXOPs) are to be allocated. The SP selector examines the queue status and selects the non-empty queue with the highest priority. The FQ selectors examine the queue status and select a non-empty queue in a fair queuing manner. As indicated in the following figure, “C2” traffic has the highest priority in a strict-priority sense within all the 3 TCs. High priority data is the second highest priority and the regular data has the lowest priority. The “C2” traffic and high priority data amongst the set of TAs compete for TXOP in a FQ manner. Regular data from various TAs competes for TXOP in a strict priority manner. This example realizes QoS for C2, data with various priorities and prioritization per TA within a test range at the GS.

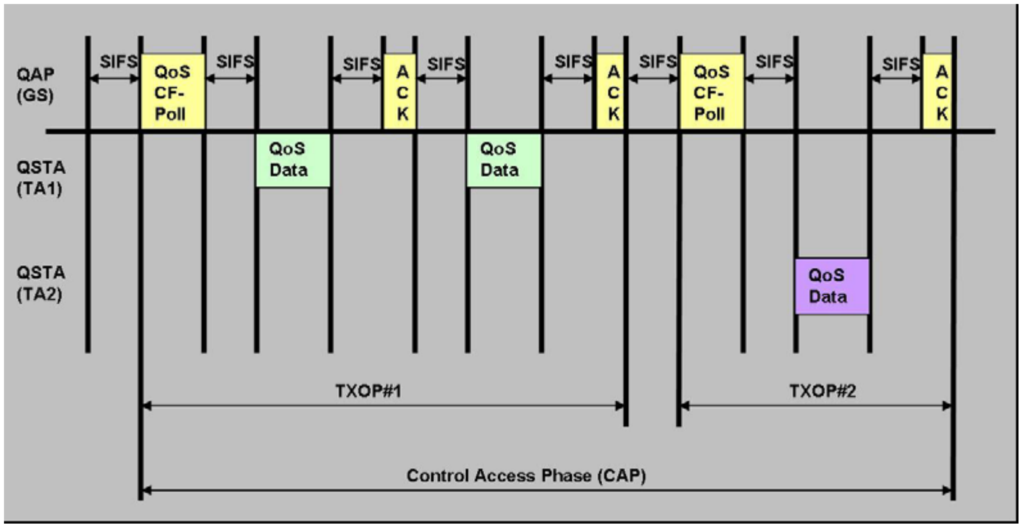

Figure 2 Control Access Phase (CAP) timing example for two TAs scheduled QoS Data with GS

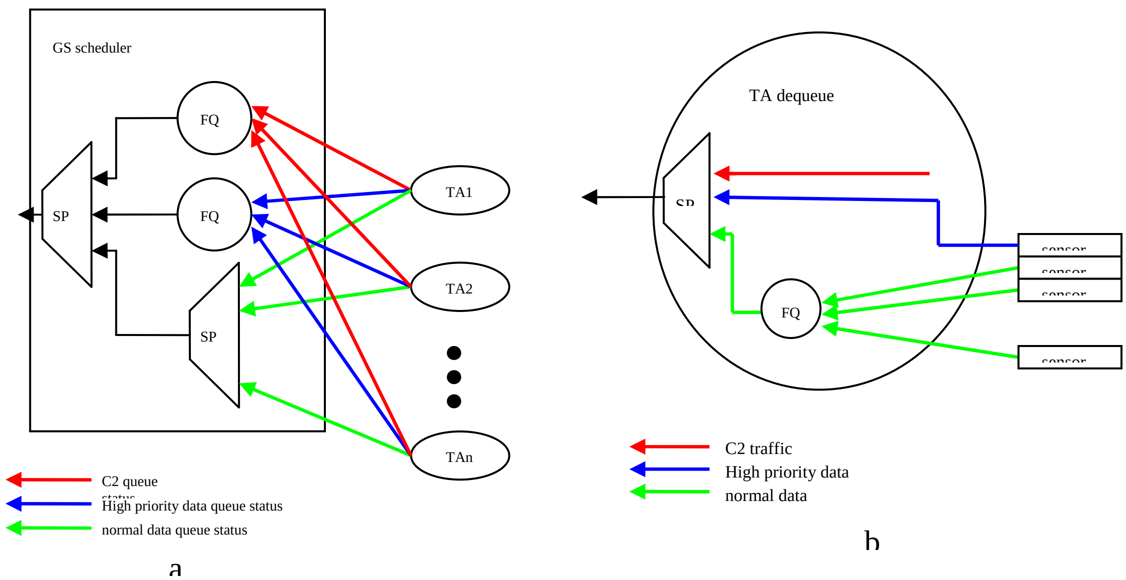

Figure 3 a) GS QoS Scheduler for TA to GS TXOP coordination b) TA scheduler for multi-sensor, and multiple onboard packet telemetry with varying priority traffic

Upon the reception of a TXOP, the TA is to properly dequeue traffic. The dequeue controller onboard the TA is required to complete the QoS realization. Recall as depicted in Figure 3a above that the GS (operating as the HC/QAP) can perform a QoS poll to the respective TAs (operating as QSTAs) to allocated time slots for the prioritized data. If no high priority data is available at the QSTA (e.g. the Test Article of interest) then the QSTA notifies the QAP with a QoS Null allowing termination of the TXOP and if higher priority traffic is available on a second TA, earlier access time is allowed to the second TA with higher priority traffic. For onboard processing of a single TA, we present the example of a simple dequeue controller shown in Figure 3b consisting of a SP selector and a FQ selector. In this example, the "C2" traffic competes for the TXOP as the highest priority candidate. One of the sensors is assigned the high priority data, competing as the second highest priority for the TXOP. The other sensors compete at the lowest priority after being selected amongst the others in a fair queue manner.

<u>Preliminary MAC Analysis</u>

We now provide some preliminary calculations based on the most fundamental frame structure for the control access phases corresponding to a number of TXOPs where each TXOP contains a Contention Free Poll (CF-poll) period from the GS (CFPP), a SIFS period (SIFSP) and the TA QoS Data period (QDP). Specifically, the Throughput efficiency is as follows

$$Throughput = \frac{QDP}{CFPP + SIFSP + QDP}.$$

The SIFS period is a roundtrip cycle worst case delay of ~160 km /3x10^8 m/s = 0.5 ms. The CF-poll period is on the order of 10^3 bit (poll message max size /20 x10^6b/s = 1/20x10^3 = 0.5 x 10^-4 = 0.05 ms.

Assuming that the QoS packet data access are on the order of 5 ms (~100 kb on the order of a single IP packet) data access blocks, then the throughput efficiency is 5ms/5.55 ms = 0.9 or 90% efficiency.

Assuming that the QoS packet data access was equivalent to bursting 10 IP packets (50 ms burst periods of data), then the throughput efficiency is 50/50.55 = 0.99 or 99% efficiency

2.2 PRELIMINARY MULTI-HOP NETWORKING

The key object is to achieve integration of networking functionality supporting mobility and multi-hop routing for improved iNET coverage under a variety of test configurations while maintaining high bandwidth efficiency and precise timing control. To meet this object, we adopt an 802.11-based Mesh Network approach where routing and mobility functionalities are jointly implemented by layer 2 and 3, thus achieving overhead reduction while retaining the flexibility of legacy 802.11. The ***802.11s Mesh extension*** is under development to provide multi-hop capabilities over a wide range of operating environments, with high efficiency and flexibility, enabling hybrid profiles and rapid reconfiguration for a variety of test environments with a single solution base.

Due to a strong requirement on efficiency and mobility support, it is desirable to shield the IP layer from tracking the dynamics in the link and physical layers and therefore minimize processing and uncertainty in transmission latency. By handling the multi-hop relay in the link layer, we take advantage of the fact that the link layer has more information about the physical environment and tighter integration with the radio for efficient utilization of the RF resources. Within the iNET architecture, the usage of IP provides interoperability to external entities and networks. From a technical stand point, any solution adopted for meeting iNET-specific requirements and environments should be completely transparent to IP so interoperability with external networks is not compromised[1]. The use of IP provides a higher level of independence between the different link/physical “profiles”. Gains in bandwidth efficiency and timing control are achieved by integrating the Mesh extension with the 802.11e HCCA (HCF Control Channel Access) which provides TDMA-like operations while co-existing with 802.11a,b,g’s flexibility. Three approaches for Mesh networking are currently under consideration by the 802.11s TG for further development: Mesh Network Alliance (Philips & ComNets), Wi Mesh Alliance (Accton, InterDigital, MITRE, Nortel, Naval Research Lab, et. al.), and Simple Efficient Extensible Mesh (SEE-Mesh) - Qualcomm, Fujitsu Lab, Intel, Nokia, etc. The 802.11 MESH approach, from a functional perspective, meets the need for flexible and efficient, multi-hop and mobile networking for iNET applications. Adoption of a form of these mesh approaches will provide for mot of the needs in the Aeronautical environment. However, several key topics require further incorporation into the architecture.

Bandwidth Efficient Relay Scheduling & Interference Avoidance:

To achieve TDMA level bandwidth efficiency for Mesh transmission, it is crucial that mesh traffic should be serviced during the contention free period (CFP). By maximizing the number of Mesh Transmission Opportunities (MTxOPs) requested per message, the scheduling/negotiation overhead can be amortized over a long period of time. It is also possible to bypass the entire negotiation process if the MTxOP occupancy map for each mesh point (MP) can be pre-loaded and updated from a central controller. This will provide the maximum degree of control over bandwidth assignment and efficiency when the mission configuration is fairly static. Note that this still can fit into the regime of on-demand priority for multiple TAs. When no explicit resource assignments are provided, the MP scheduling algorithm can automatically generate an efficient schedule for the Mesh based on observed traffic on demand.

The aeronautical network environment is pre-dominantly a collection/distribution network. Sensor data is collected from multiple TAs, and the commands generated by the GS are disseminated to the TAs as envisioned by iNET. Specialized scheduling approaches can be used to exploit the structure of this traffic pattern to minimize latency and optimize efficiency by compensating for different propagation delays. An optimal scheduling algorithm for such collection/distribution network has been developed by [CFlorens], and then [ClareSCP] extended and applied it to the space networking context where a constellation of satellites perform a TDMA-based multi-hop relay network to collect sensor readings from the Earth’s magnetosphere [ClareSCP]. Such optimized scheduling can be similarly computed and disseminated throughout the mesh network to optimize its performance in the aeronautical network environment.

It is noted that consideration of the proper adjustment of 802.11x parameters is required to compensate and allow application to environments extending the geographical range and time-bandwidth product of the original standard. In our previous work, [ClarePFF]

[1] As part of this would be the use of security exchange of packets such as IPsec or in some cases layer 3 Type 1 encryption techniques. Furthermore, issues concerning Multiple Independent Levels of Security (MILS) are also being considered but are outside the scope of this paper.

applied 802.11 networking solutions to space-based precision formation flying missions, determined that very modest degradation occurs to the 802.11 MAC protocol for networks with large inter-node distances.

For iNET applications, a two-tier scheduler design can be used to determine the order by which all packets will be serviced by the HCCA. For example Figure 4 on the following page depicts the intra-cluster scheduler for the 802.11e HCCA at a TA. The scheduler queues data arriving from the Mesh, from intra-cluster traffic generated by associated TAs, and traffic generated by its own local TA. The de-queue controller uses a weighted fair queue (WFQ) algorithm to select data per TXOP for transmissions between two sub-dequeue controllers according to pre-assigned weights. The top sub-dequeue controller handles traffic arriving from other TAs, either from the Mesh tier or within the same cluster; the bottom sub-dequeue controller handles local TA's data. In this example, the assigned weights are used to divide the RF resources proportionally between mesh traffic and locally generated traffic. The Fair Queue (FQ) and Strict Priority (SP) algorithms for the top sub-dequeue controller in the figure can also provide finer access control over the out-bound channel between neighboring mesh point TAs and TAs within the same cluster as depicted in the figure by the different colored lines from the TAs.

For iNET, the near term aeronautical scenarios will most likely have slow topology changes where a proactive routing algorithm, one that periodically updates the network routes, provides low overhead and quick response time. Since the current 802.11s proposal approaches feature a combination of an on-demand and proactive routing algorithm, at least two appear to be well-suited to handle future iNET scenarios involving a large number of dismounted war-fighters, ground vehicles, etc.

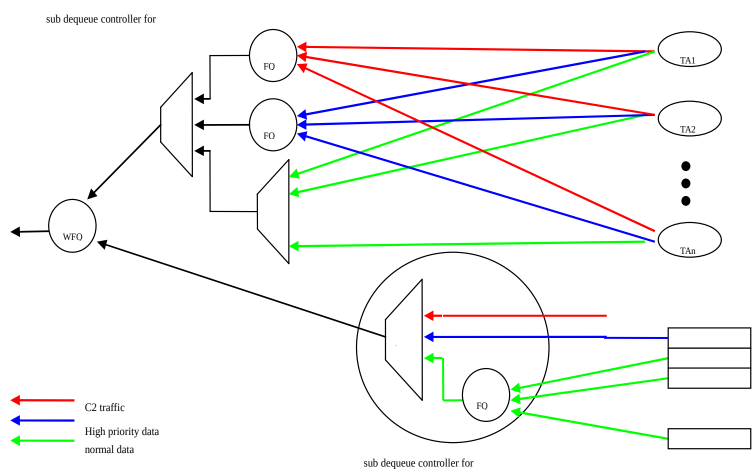

Figure 4: BSS scheduler at a Mesh Point

There are special considerations that are known to arise for airborne networks due to their RF link characteristics. Considerations at Layer-3 include sub-network membership. The sub-network may be organized so not all members can talk to each other. For example, a transmission from the hub may be received by all spoke nodes on the sub-network, but a transmission by a spoke node may only be received by the hub. This has implications to IP neighbor discovery, unicast and multicast protocols. If IP were used as part of the TDMA structure, this problem would have to be addressed and translate to unique configurations for the IP layer protocols. In extreme cases if the test platform were to fly 100 miles, it could handover to a different (possibly commercial) access point and the experiment would not lose network layer routes.

III. Discussion

Work will continue investigating the burst modem performance metrics against the layer-2 MAC for TDMA and packetized data needs. In the multi-hop regime, interference avoidance is an issue when the physical layer uses wide-beam or omni-antenna for signal transmissions. The 802.11s beaconing and channel scanning process can be used to generate an interference topology as an additional constraint on the Mesh scheduler. Due to the unique nature of the aeronautical environment an interference model, or "world" model, that describes the propagation environment and presence of obstacles, should be developed and integrated into each MP, possibly even augmented by GPS information. To further assist in the mitigation of interference, the beacon message is used to exchange MTxOP occupancy maps (schedules) beyond the 1-hop neighborhood so that problems with hidden terminals can be discovered and resolved during the scheduling process.

Other issues of concern are security and layer-4 issues such as TCP/IP and/or other reliable transfer protocols (e.g. SCTP, off-shoots of Disruptive and Delay Tolerant Networking) and the above applications. As the iSENET architecture is refined, these issues will be resolved to provide for netcentric quality of service telemetry needs.

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