PERFORMANCE EVALUATION OF A TDMA MAC PROTOCOL IN AIRBORNE TELEMETRY NETWORKS

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ABSTRACT

Emerging airborne telemetry networks are going beyond traditional point-to-point communication. The iNET telemetry architecture uses a TDMA MAC with relay nodes that enable multi-hop communication. We analyze the performance of the iNET TDMA MAC protocol with respect to various parameters such as number of nodes, flight range, number of relays, and number of hops via mathematical modeling. We also discuss the role of cross-layer optimizations with the AeroNP, AeroRP, and AeroTP aeronautical protocols.

I. INTRODUCTION

With the recent advances in communication systems, and the increased demand for telemetry applications, the Central Test and Evaluation Investment Program (CTEIP) launched the integrated Network Enhanced Telemetry (iNET) program to re-engineer traditional telemetry networks. The airborne telemetry environment has unique characteristics including highly mobile airborne wireless nodes, limited bandwidth, and long flight ranges [1]. Time division multiple access (TDMA) allows medium access to the nodes sharing a wireless channel assigning fixed time slots, eliminates collisions, and provides fairness. However, this may result in low utilization of the bandwidth due to idle slots if some nodes do not have data to transmit [2]. TDMA is widely used in personal communication systems (PCS), 2nd generation digital cellular communications systems, as well as wireless sensor networks (WSN) [3], [4], [5], [6].

Various TDMA algorithms can be designed for single-hop or multi-hop networks, using node or link-allocation-based schemes, and using centralized or distributed algorithms [7], [8], [9]. The distributed algorithms can benefit from spatial reuse, but are hard to design due to slot synchronization and high mobility [10], [5], [11].

The iNET TDMA MAC [12] is a centralized TDMA algorithm designed for the telemetry environment that allows assignment of variable length transmission opportunities (TxOp) to test article (TA) nodes to have higher utilization of the bandwidth and proposes relay nodes (RN) for multihop communication. In this work, we develop a mathematical model for the iNET TDMA MAC frame, analyze the performance of the protocol, and discuss cross layering issues.

The remainder of this paper is organized as follows; section II explains the operation of the iNET TDMA MAC protocol, section III formulates the frame model, section IV presents the results, section V discusses the role of cross layering, and the paper is concluded in section VI.

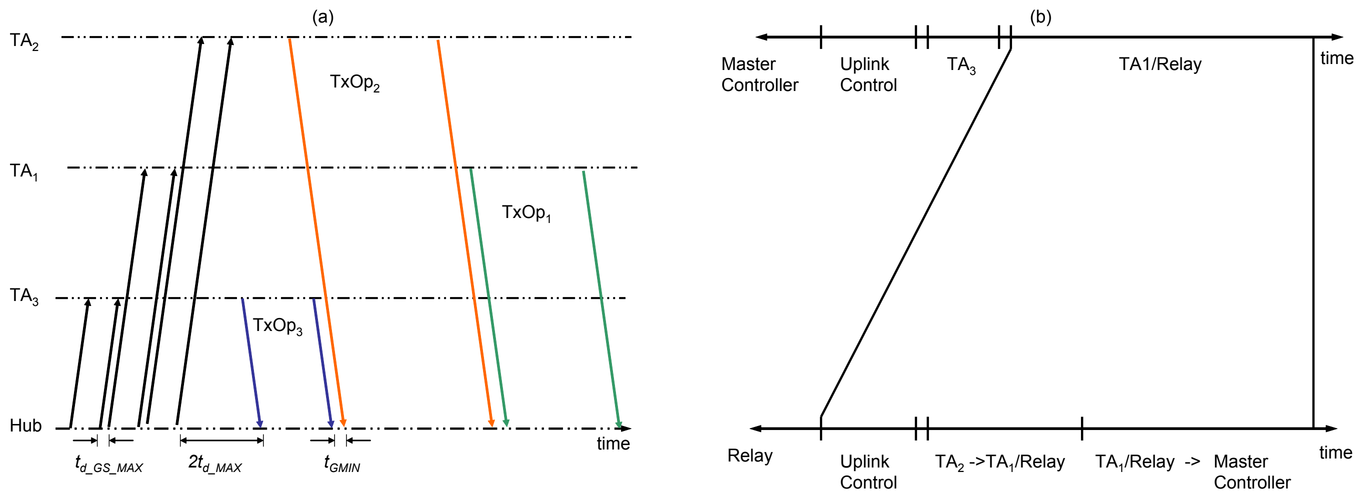

Figure 1: TxOp assignment within a iNET TDMA MAC frame [12]

II. iNET TDMA MAC

A. TxOp Assignment

Highly dynamic mobile TAs that are tracked by ground stations (GS) form the aeronautical telemetry environment [1]. The master TDMA controller that resides on ground assigns transmission opportunities (TxOps) to TAs via GSs or RNs. RNs form TDMA subnetworks that enable multihop communication for its member TAs that are not in the transmission range of the GSs. Uplink communication is the communication from a subnet controller to one of its members, and downlink communication is from a subnet member to its controller. The iNET TDMA MAC frame starts with a sequence of uplink communications in which control packets are sent to the member TAs that denote the start time and the duration of their TxOp within that frame. TAs have an externally referenced GPS device for time synchronization and TxOp assignment. At least one control packet is sent to each TA in each frame that includes the TxOp information for that TA. Uplink transmission is followed by downlink in which TAs transmit packets to their subnet controllers. Similarly, each TA sends at least one control packet to its controller in each frame that denotes its queue status, which affects the TxOp assignment for the next frame. This operation is shown for a single hop network with three TAs in Fig. 1(a), where *hub* denotes the master TDMA controller.

Fig. 1(a) also shows the guard times within a frame. The $t_{\mathrm{d\_GS\_MAX}}$ is the guard time between two uplink transmissions and is the propagation time of a signal to travel the maximum distance of two antennas. The t_{GMAX} is defined as the time between uplink and downlink transmissions that is the maximum round trip propagation time considering a TA at a maximum range that is shown as $2t_{\mathrm{d\_MAX}}$. The t_{GMIN} is the minimum guard time assigned to TAs that perform range compensation. The TAs that do not perform range compensation are assigned $t_{\mathrm{d\_MAX}}$ duration of time between two downlink transmissions that accounts for the TA at a maximum distance.

B. Relay Nodes

In the case where RNs are present to allow multihop communication, the master TDMA controller sends a control packet in the beginning of the frame to the RN that includes the TxOp information for that

RN. As the master controller assigns the TxOps for TAs and RNs that are in its network, a RN assigns TxOps in its TDMA subnetwork to its members via the same control packets in the beginning of its sub-frame as in Fig. 1(b). The RN forwards the data packet of a TA in its subnetwork to the destination GS.

III. FRAME MODEL

In modeling the iNET TDMA frame, we make several assumptions. We assume a fixed data packet size for nodes that have data to transmit and a fixed 46 byte control packet that is long enough to include TxOp or queue length information. High level data link control (HDLC) is proposed in the iNET TDMA MAC protocol for link layer framing that adds 3 Bytes of header and 1 Byte of flag sequence to the formatted payload which consists of IP datagram, 14 Byte Ethernet header and 4 Byte CRC checksum. we assume that one out of 64 Bytes are replaced with a 2 Byte sequence during byte stuffing. The probability that a 1 Byte sequence will be identical to one of the two 1 Byte flag or escape sequences is 1/64. Also, we assume that there is t_{GMAX} duration of guard time between two iNET TDMA MAC frames or sub-frames. Finally it is assumed that uplink communication is for control traffic only, downlink communication is for control and data traffic, and all the data traffic is from the TAs to the GSs. We then define the following variables :

N_{t} : Total number of nodes
N_{a}: Number of active nodes that have data packets to transmit
N_{p}: Number of passive nodes that do not have data packets to transmit
N_{r}: Number of relay nodes
N_{rn}: Number of nodes that are within each RN's sub-network.
N_{rc}: Number of nodes that perform range compensation
N_{nrc}: Number of nodes that do not perform range compensation
D: Flight range, maximum distance between two radios [nmi] (nautical mi)
P_{i}: IP data packet size [bytes]
P_{h}: HDLC size, encapsulated IP data packet size [bytes]
P_{u}: Uplink control packet size [bytes]
P_{d}: Downlink control packet size [bytes]
R_{u}: Uplink data rate [b/s]
R_{d}: Downlink data rate [b/s]

Based on the iNET TDMA MAC frame structure and the parameters defined above, a frame consists of uplink control messages transmitted by the ground stations followed by downlink control and data transmission. If there is no range compensation done, and there are no relay nodes, the time duration of a TDMA frame can be defined as follows:

$$\begin{aligned} F &= 8N_{\text{t}}P_{\text{u}}/R_{\text{u}} + (N_{\text{t}}-1)t_{\text{d\_GS\_MAX}} + t_{\text{GMAX}} \\ &+ (N_{\text{t}}-1)t_{\text{d\_MAX}} + 8N_{\text{a}}(P_{\text{h}}+P_{\text{d}})/R_{\text{d}} + 8N_{\text{p}}P_{\text{d}}/R_{\text{d}} \end{aligned}$$

which consists of uplink control messages, uplink guard times, guard time between uplink and downlink transmission, active nodes' downlink data and control messages, and passive nodes' downlink control messages. When range compensation is done, instead of $(N_{\text{t}}-1)t_{\text{d\_MAX}}$ being the total duration of guard

times at the downlink, $N_{\text{rc}} t_{\text{GMIN}} + (N_{\text{nrc}} - 1) t_{\text{d\_MAX}}$, will be the total duration of the guard times where t_{GMIN} is half the duration of $t_{\text{d\_MAX}}$ assuming the expected value of the range for a node is simply $D/2$. Here we also make the implicit assumption that one of the nodes that do not perform range compensation is assigned to transmit first in the beginning of the downlink transmission by the master TDMA controller to minimize the guard times within a frame.

In this frame structure, the maximum achievable throughput is the case where a data transmission is followed by a downlink guard time, where there is no control traffic. We will denote this case to be the theoretical maximum and compare the performance of the iNET TDMA MAC to this maximum achievable throughput to see the effects of various parameters on the performance. We define the normalized throughput as the following:

$$\begin{aligned} R_{\text{n}} &= R/R_{\text{d}} \\ &= (8N_{\text{a}}P_{\text{h}})/(R_{\text{d}}F) \end{aligned}$$

demonstrating the ratio of R compared to R_{d} where R is the actual number of data bits sent in one second, R_{d} is the downlink data rate, and F is the time duration of the TDMA frame.

In the presence of RNs, assuming all nodes are active, the TDMA frame also includes sub-frames that are similar to a single hop TDMA frame as defined above. The main difference here is that there are twice as many data packet transmissions at the downlink as in the single hop case, one from the TA to its relay, and one from the relay to the GS. The time duration of a sub-frame is then defined as:

$$\begin{aligned} F_{\text{s}} &= 8N_{\text{rn}}P_{\text{u}}/R_{\text{u}} + (N_{\text{rn}} - 1)t_{\text{d\_GS\_MAX}} + t_{\text{GMAX}} \\ &+ (2N_{\text{rn}} - 1)t_{\text{d\_MAX}} + 8N_{\text{rn}}(2P_{\text{h}} + P_{\text{d}})/R_{\text{d}} \end{aligned}$$

Also we can define N_2, the number of two hop nodes as $N_{\text{r}}N_{\text{rn}}$ and N_1, the number of one hop nodes as $N_{\text{t}} - N_2$. Then we can define the time duration of a TDMA frame in the presence of relay nodes as:

$$\begin{aligned} F_{\text{r}} &= 8(N_1 + N_{\text{r}})P_{\text{u}}/R_{\text{u}} + (N_1 + N_{\text{r}} - 1)t_{\text{d\_GS\_MAX}} + t_{\text{g\_MAX}} \\ &+ 8N_1(P_{\text{h}} + P_{\text{d}})/R_{\text{d}} + (N_1 - 1)t_{\text{d\_MAX}} + N_{\text{r}}F_{\text{s}} + N_{\text{r}}t_{\text{g\_MAX}} \end{aligned}$$

This frame consists of uplink control, followed by $t_{\text{g\_MAX}}$ guard time between uplink and downlink transmission, data and control transmissions of one hop nodes with appropriate guard times, RN sub-frames and guard times between sub-frames.

IV. SIMULATION RESULTS

The default values used for all simulations if not varied include a flight range of 100 nmi, uplink and downlink data rates of 1 Mb/s, a data packet size of 1024 Bytes, and no range compensation for all nodes.

C. *Number of Nodes*

In this single hop scenario with no RNs, all nodes are active. As shown in Fig. 2(a), the aggregate normalized throughput increases from 0.70 to 0.77 with increasing number of nodes because the effect of the fixed guard times between uplink and downlink transmission, and between two frames decrease with increasing number of nodes and frame size. On the contrary, the frame size increases from 12 ms to 554 ms almost linearly as the number of nodes increase. The frame size can be an important measure in some cases where it can limit the number of nodes in the network since larger frame size may degrade the performance of delay sensitive applications.

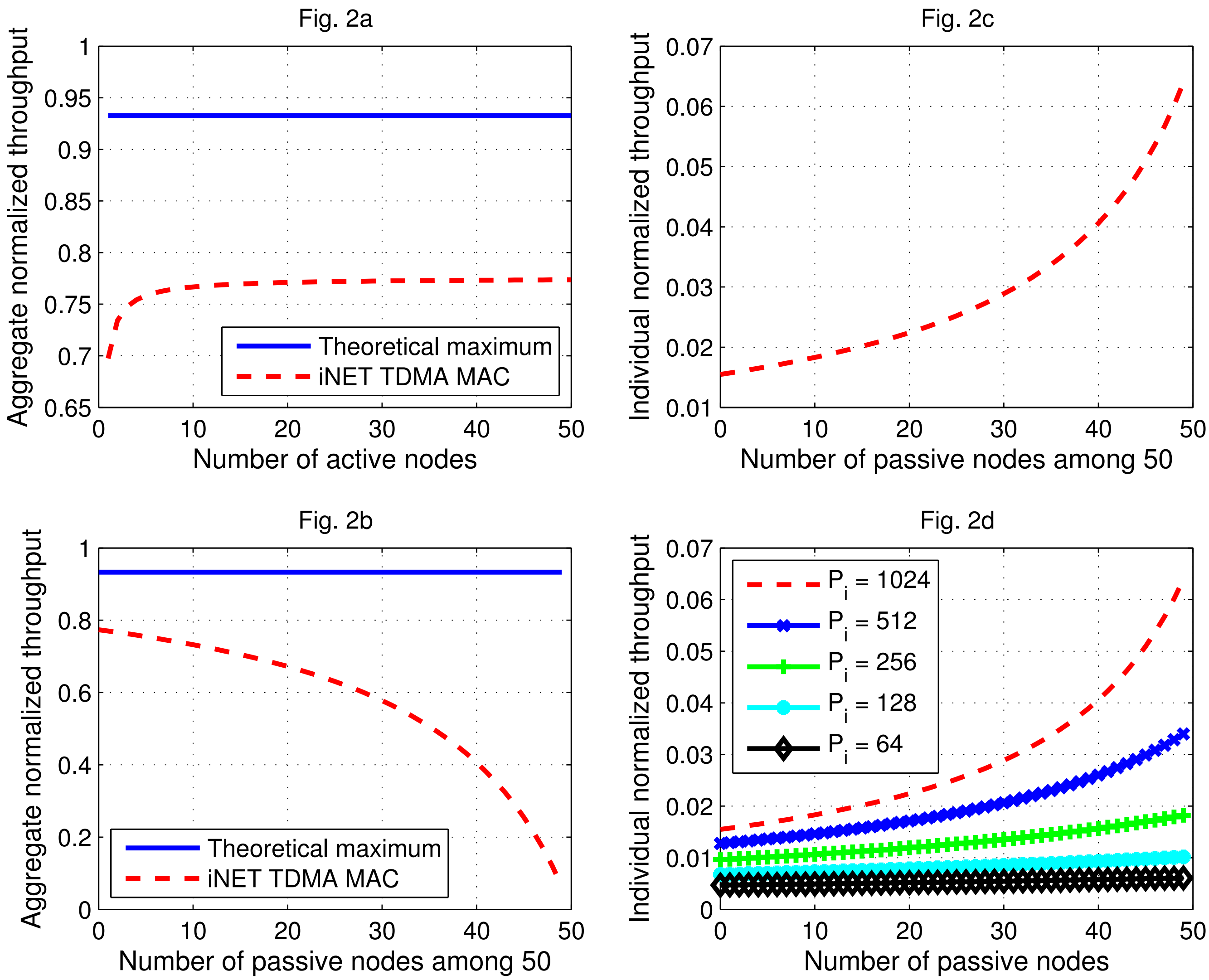

Figure 2: The effect of N_{a}, N_{p}, and P_{i} on R_{n}

D. *Number of Passive Nodes*

In this single hop scenario, there are total of 50 nodes, and the number of passive nodes among 50 nodes is changed from 0 to 49 to see the effect of passive nodes to the aggregate throughput, individual throughput, and frame size . As in Fig. 2(b), the aggregate normalized throughput decreases from 0.77 to 0.06 with increasing number of passive nodes. This is due to the increased portion of the control packets within a frame. On the other hand, because of the smaller size of control packets compared to data packets, the frame size decreases almost linearly from 553 ms to 133 ms and the individual normalized throughput increases from 0.015 to 0.063 as in Fig. 2(c). When the portion of passive nodes increase, the active nodes can have higher throughput relative to the all nodes active case simply because they transmit data packets, which are bigger compared to control packets. As in Fig. 2(d), when the IP data packets get smaller in size, the individual throughput also decreases and becomes less than the all nodes active case for IP data

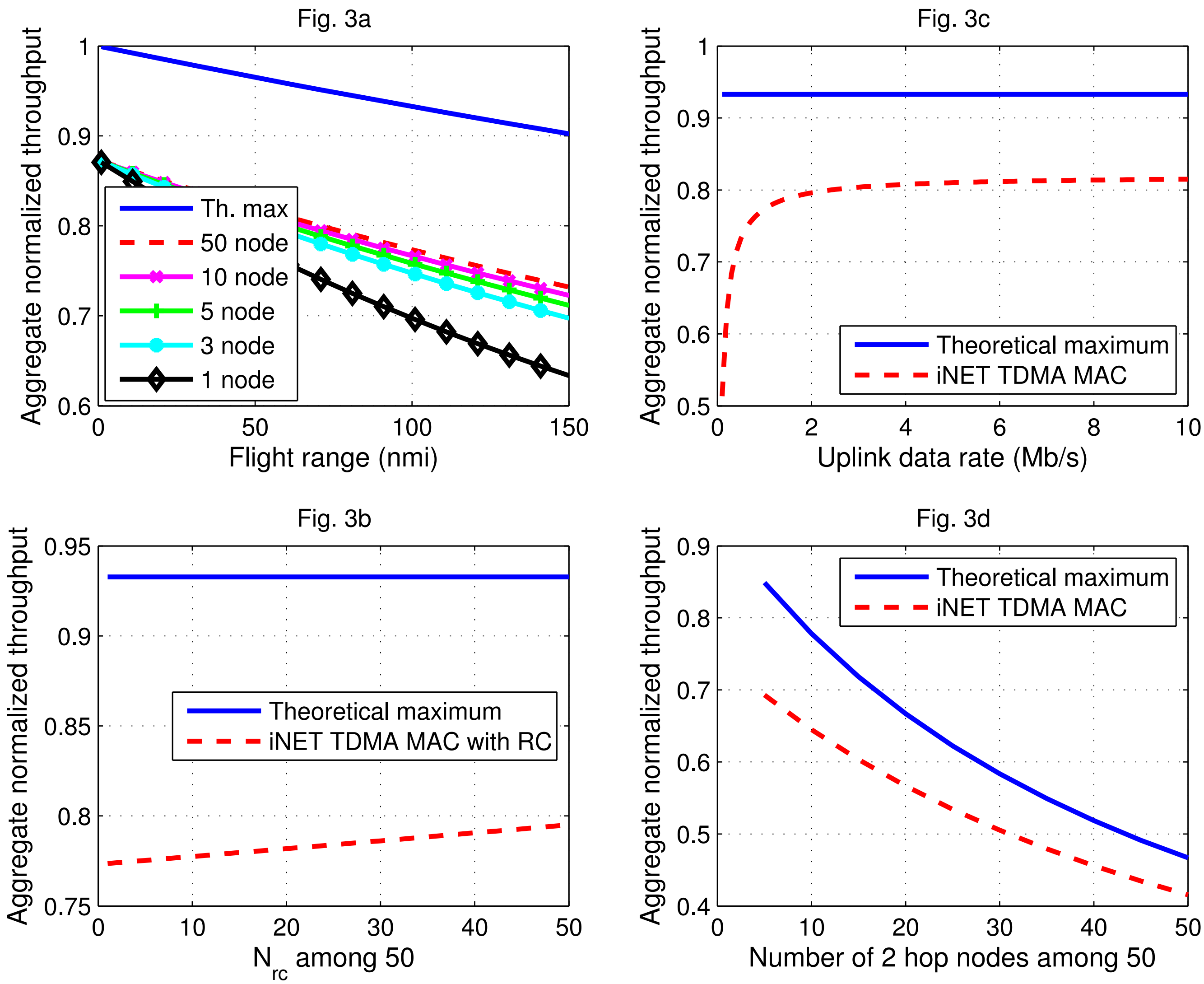

Figure 3: The effect of D, $N_{\rm rc}$, $R_{\rm u}$, and $R_{\rm d}$ on $R_{\rm n}$

packet sizes 256, 128, and 64.

E. Flight Range

In this single hop scenario, the flight range is changed from 1 nmi. to 150 nmi. for 1, 3, 5, 10, and 50 active nodes. As in Fig. 3(a), the aggregate normalized throughput decreases with longer flight ranges. This is simply because of the longer guard times needed between transmissions for longer flight ranges. Moreover, the guard times have bigger effect on the performance when number of nodes is less than 10 because of smaller frame sizes and relatively bigger portion of guard times within the frame.

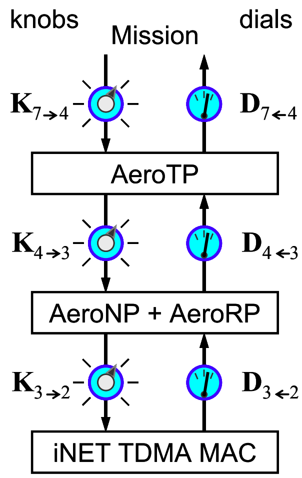

Figure 4: Knobs and dials for telemetry network stack

F. Range Compensation

In this single hop scenario, number of nodes that perform range compensation is changed from 0 to 49 for a total of 50 nodes. The aggregate normalized throughput increases from 0.77 to 0.79 with all nodes doing range compensation as in Fig. 3(b). In all cases, the range compensation improves the performance up to 2 %.

G. Uplink and Downlink Data Rates

In this single hop scenario with 50 nodes, all nodes are active, and the uplink data rate is varied from 100 kb/s to 10 Mb/s whereas the downlink rate is kept constant at 1 Mb/s. As in Fig. 3(c), since uplink communication is for control packets only and downlink is for data and control packets, having a relatively higher data rate at the uplink improves the performance because the theoretical maximum throughput is bounded by the downlink data rate only. This also means less overhead due to control packet transmissions. The gain is up to 30 % in the aggregate normalized throughput from 0.51 to 0.81 for uplink data rates 100 kb/s and 10 Mb/s.

H. Relay Nodes

In this two hop scenario with 50 nodes and 5 RNs, the number of nodes that each relay has in its own sub-network varied from 1 node to 10 nodes. With increasing number of two hop nodes, the aggregate normalized throughput decreases from 0.69 to 0.41. This is because there are twice number of transmissions from a two hop TA to reach the destination GS, and there is no spatial reuse. The theoretical maximum normalized throughput in Fig. 3(d) is also calculated assuming no spatial reuse, and it can be considered as a lower bound on the theoretical maximum aggregate normalized throughput. Note that this only permits single hop relaying through RN. A general multihop capability through TAs and RNs out-of-range of a GS is provided by AeroNP, and AeroRP [13], [14], [1].

V. CROSS-LAYERING

Cross-layering mechanisms can be employed in wireless networks rather than strict layering to improve the overall performance of the network with a careful integration amongst the layers. The transport, network and data link layers of the aeronautical protocol suite are AeroTP, AeroNP and AeroRP [1], and iNET TDMA MAC respectively as shown in Fig. 4. The cross-layering mechanisms enable the dials $\mathbb{D}$ to instrument information from below to the higher layer, and the knobs $\mathbb{K}$ at higher layers influence different mechanisms at the lower layers. The dials from iNET TDMA MAC to the upper layer AeroNP and AeroRP include location and speed information of the TA, link capacity, frame error rate, and queue length, whereas the dials from AeroNP and AeroRP to the upper layer AeroTP are path frame error rate, path capacity and path throughput. The knobs from AeroTP to AeroNP and RP include the reliability mode and error control requests to the link layer, whereas the knobs from AeroNP and AeroRP to iNET TDMA MAC are priority indication for queues and error control requests to the link layer.

This cross-layering is crucial for the operation of AeroTP [15], [16], and AeroRP [13], [14]. In particular, AeroTP uses an adaptive flow-control mechanism called *backpressure*, which is implemented as part of AeroNP. AeroNP signals AeroTP to reduce its sending rate based on information that is gathered by the MAC-layer snooping mechanism. AeroTP also adapts its error control mechanisms and signaling based on the reliability mode derived from the mission as well as dials propagated from the MAC up through the network layer to adjust parameters such as FEC strength. The priority and type of data segment transmitted are dictated by the mission and communicated from the application layer, to AeroTP, and from there to AeroNP, to be stored in the network layer header to enable appropriate QoS decisions at each hop. Finally, AeroRP relies on geolocation information supplied by external physical devices for its operation.

VI. CONCLUSION

In this work, to evaluate the performance of the iNET TDMA MAC protocol, we formulated a mathematical model for the frame and sub-frame structure and discussed the role of cross layering.

Simulation results show that greater number of active nodes may increase the aggregate throughput with a penalty of decrease in individual throughput and longer frame duration. Also, having greater number of passive nodes may increase the individual throughput for big data packet sizes and have a shorter frame duration with a penalty of significant decrease in aggregate throughput. Moreover, longer flight ranges result in longer guard times and decrease the aggregate throughput, whereas range compensation can make little improvement in the aggregate throughput. Finally, slower uplink data rates compared to downlink data rate, and greater number of two hop nodes significantly degrade the performance, because in the former case, the control traffic is sent at a much slower rate resulting in bigger control traffic overhead, and in the later case, data packets has to be transmitted twice, and there is no spatial reuse. Overall, our work provides a mathematical model and performance evaluation for the iNET TDMA MAC, which is designed specifically for highly mobile aeronautical networks.

In the future work, we will implement iNET TDMA MAC in the ns-3 network simulator, analyze the performance of the overall protocol suite with AeroNP and AeroTP, and investigate the cross-layering issues in conjunction with the ns-3 AeroNP, AeroRP, and AeroTP models.

ACKNOWLEDGMENT

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