Analyzing Impact of TDMA MAC Framing Structure on Network Throughput for Tactical MANET Waveforms

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Abstract- With the advancement of networking technology it is anticipated to have Internet like functionality in tactical network. However, unlike commercial network the tactical networks operate under severe environment and resources constraints. Moreover, the MANET architecture and shared resources of wireless medium further put limitation on network design for high throughput. The access to the shared radio channel, within the mobile ad hoc network is managed by the medium access protocol (MAC). To achieve greater capacity and enhanced performance in the network, dynamic TDMA MAC is employed in tactical MANET waveforms.For such waveforms an important operational requirement is to address a variable number of nodes in a network to support the scalability of tactical deployment and have provision to respond promptly to voice calls with a short delay and small jitter.However, the large radio range and incorporation of ECCM further complicate the MAC frame design. In this paper, we analyze all these constraints for MAC frame design and demonstrate how it affects the network throughput.

Keyword: *Tactical network, MANET, MAC, TDMA, Framing, network size, channel constraints*

I. INTRODUCTION

In tactical network, radio nodes operate under severe environment constraints. Such region is highly dynamic in nature, consisting of a variety of network elements, largely comprised of mobile wireless nodes. In such environment the Tactical Data Link (TDL) based MANET systems provide a means for rapid exchanges of tactical digital information between air, land, sea and command center units as illustrated in figure 1. A TDL system is the key component in providing situation awareness in a modern warfare and interoperability between different systems[1,2].

Figure1:Tactical Network

The TDL system waveform is governed by a MAC protocol and a physical link technology enablingdigital data to be transferred from one source to other destinations through a communicationchannel. To enable the sharing of a channel in aTDL system among members, an efficient medium access protocol (MAC) must beimplemented.

One approach for MAC design is, to use the time division multiple access (TDMA) protocol, whereeach node transmits or receives at given time slots. TDMA protocols being a scheduled MAC protocol are potentially better suited to networks with heavy or unbalanced load [3]. The TDMA MAC also suits to tactical MANET environment because of its capability to support QoS, which is not guaranteed in contention protocols [4].In static TDMA schemes the node's time slot gets wasted when it does not have traffic to transmit. That's why a mechanism that conserves the channel bandwidth is needed in such scenarios. Moreover, in a fully connected network, it comes natural that the channel bandwidth is evenly shared among all nodes using a suitable MAC protocol; because the priorities of nodes or links are uniformly distributed. However, in tactical ad hoc network, where nodes are randomly placed over an irregular plane, bandwidth allocation to a node is much more complex.

To achieve greater capacity and enhanced delay performance in the network, dynamicTDMA scheme is employed at the MAC layer [5,6]. In dynamic TDMA,which is an extension of TDMA, time is divided into time slots.Multiple transmissions can be scheduled as long as the receiving nodes do not get their packets interfered with. In this manner, dynamic TDMA takes advantage of the spatial separation between nodes to reuse the time slots.Generally, such schemes require strict time synchronization among participating nodes for efficient transmission and reception among the nodes. In addition, as a result of mobility of nodes in MANETs, periodic changes in the network require that the schedulesfor transmission rights of nodes must be updated with minimal latency andcomputational complexity. Furthermore, the updated schedule must be propagated to all nodes in the network in a timely and efficient manner.

The literature is rich with work conducted in the area of scheduling and synchronization for MANETs. Several survey articles and research work have been published on MACscheduling and synchronization schemes from different perspectives indicate the continuing challenges in this topic area. However,there is a lack of published models and references in one important aspect of MAC, which is, Framing of TDMA slot structure and its impact on network performance. We consider it as one of the critical areas of MAC design for tactical environmentsbecause unlike the commercial MANET, in tactical environment we talk about of the radio range in hundreds of kilometers with limited channel data rate,as is the case with airborne network.

In tactical MANET waveforman important operational requirement is to address a variable numberof nodes in a network to support the scalability of tactical deployment caused mainly due to mobility of nodes. Furthermore, the MAC protocol must have provision to respond promptly to voice calls so that it can be served with a short delay and small jitter as voice is the primary service in narrowband MANET waveform [7].The large radio range of tactical waveforms requires large propagation delay margin,which sets constraints on smaller slot size, while for the fast frequency hopping the smaller slots are desirable to enable effective ECCM. In this paper, we analyze all these constraints for MAC frame design and showed how it affects the network throughput for tactical MANET waveforms.

The rest of the paper is organized as follows. Section II describes the dynamic TDMA frame structure. This highlights the impact of network size and frame duration on throughput. Section III describes the internal structure of TDMA slots and shows the impact of propagation guard and frequency hopping on network performance before concluding in section IV.

II. DYNAMIC TDMA FRAME STRUCTURE

Thedynamic TDMA protocols divide the channel into network control slots(NCS) and data slots as shown in figure 2. The NCS are for sharing the critical network informationnecessary to dynamically assign the rest of the slots.

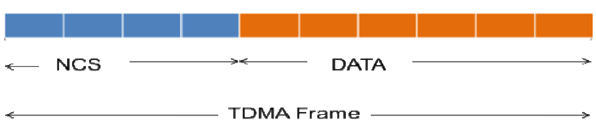

Figure 2: Dynamic TDMA Frame Structure

The data slots are dynamically allotted to the nodes based on theirtraffic need and priority. The dynamic TDMA protocol exploit the spatial reuse of the radio channel for data slots to enhance the channel bandwidth efficiency, while the control slots arestatically assigned to the nodes to support QoS. In tactical environment the number of nodes keeps joining or leaving the network due to mobility, therefore some fixed numbers of net joining slots(NES) are also required in TDMA MAC frame[8,9] as shown in figure 3.

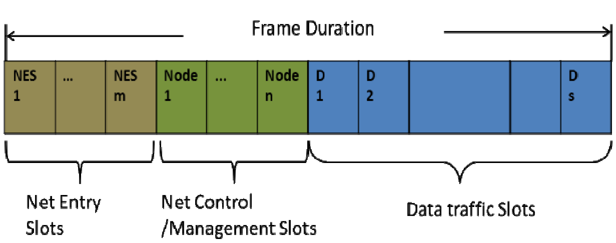

Figure 3: TDMA Frame with NES

In this structure the bits sent in datatraffic slots only contributes to the application throughput, while the NES and NCS are the overhead essential to manage the dynamism of the network. In such frame structure to support a large number of nodes, it is desirable to keep the frame duration sufficiently large to minimize overhead due to NES and NCS. The number of NES is fixed in a designand theNCS is network size dependent parameter, required by each node for exchanging its management information and for traffic slot negotiations. Therefore, if the frame duration is kept large, it adversely affects the latency requirements of control as well as ofuser traffic. Since the latency requirements for critical communication services are predefinedfor most of the tactical application [10], the frame duration can be decided on that basis. The number of nodes supported and traffic data rate,pushesthe channel rate required to meet the application data rate. This places constraints on radio modem design and RF channel bandwidth.

Let's define in a TDMA frame thereare, N_m, number of net entry slot.N_r, is the NCS to support maximum n numbers of node and D_s are the total numbers of data slots to support application traffic.$T_f$is frame duration and S is the duration of one slot in the frame.

$D_s$are the slots, which contributes to network throughputcan also be written as:

$$D_s = \left(\frac{T_f}{S}\right) - (N_n + N_m) \quad \text{-(1)}$$

If the channel rateisR_b, the network throughput N_{th}, depend on the following parameters:

$N_{th} \propto R_b * (D_s * S)$, can also be written as shown in equation 2.

$$N_{th} = K[\,R_b * S\{\left(\frac{T_f}{S}\right) - (N_n + N_m)\}] \qquad \text{-(2)}$$

Where K is the proportionality constant, which depends on the type of FEC, modulation and other PHY overheads.

Now, as the required throughput for a tactical application is also predefined and provided as an input parameter to the network designed,for example like 256 Kbps Video, 16Kbps CVSD voice[11].We now compute how it affects the channel rate for various network sizes for a constant network throughput.

If the network throughput requirement is N_{th},then required channel rate$R_b$can be computed by equation 3.

$$R_b = N_{th}/K[\,*S\{\left(\frac{T_f}{S}\right) - (N_n + N_m)\}] \qquad \text{-(3)}$$

The graph between channel rate in bits/second (bps) and frame duration in millisecond (ms) is plotted in figure

4. From the graph, it is evident that for the low frame duration, if the network node size requirement is high, it demands much higher channel data rate to support same network throughput. While for high frame duration, the effect of network size is almost negligible. From this finding, we can deduce that the MAC design needs to trade-off between the network node size and latency requirement if the channel rate is fixed as is the case withimplementing networking over legacy radios.

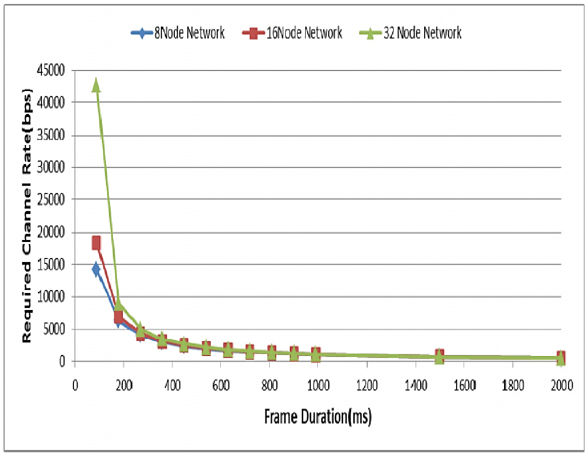

Figure 4: Channel Rate vs. Frame Duration

III. TDMA Slot Structure

Further going deep into the physical layer waveform structure, it is essential to consider the impact of guard time per slot or TX burst on network throughput. The guard time is required to cater for propagation delay, clock synchronization mismatch, MAC processing delay, frequency tuning time, TX/RX switching, power amplifier (PA) ramp up and PA ramp down along with their uncertainties. In addition to this, the slot duration must be kept sufficiently large to accommodate channels coded MAC frame plus PHY preamble as shown in figure 5.

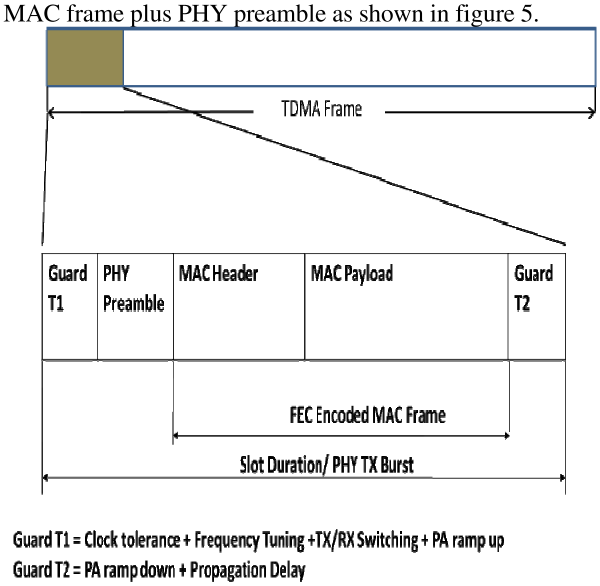

Figure 5: Physical Slot Structure

The guard time and other overheads significantly affect the effective throughput of the network. The guard time elements depend on hardware components like PA ramp up and PA ramp down etc. The major element of guard time is the propagation delay, which varies during the operation of the network. Indeed, it depends on the relative position of the communicating nodes.

The impact of guard time on throughput or MAC payload (MAC payload directly contributes to throughput), can be computed as follows:

Let's assume the MAC payload is x,MAC header isM_h, and$F_i$is the input to the FEC module in bits.Therefore, $F_i = x + M_h$

If the FEC code rate is F_r, then the output of FEC (F_o), can be calculated as:$F_o = F_i/F_r$

The total bits to be transmitted by PHY (P_o) is,

$P_o = F_o + p$, where p is the preamble size inbits.

Now assume the guard time is g. Then the slot duration (S) is equal to sum of guard time and time equivalence ofP_o.

This can also be written as:

$S = g + (P_o/R_b)$-(4)

Putting the value of P_o in the equation 4, we get.

$$S = g + \left[p + \frac{x + M_h}{F_r}\right]/R_b$$

Therefore, x can be calculated by equation 6.

$x = \left[\frac{S-g}{R_b} - p\right] F_r - M_h$-(5)

For example, assume a physical channel data rate (R_b) equivalent to 1 Mbps[12]. The slot duration is 2 ms. Physical preamble p, 64 bits, and MAC header (M_h) is of 32 bytes. FEC code rate (F_r) is assumed to be 0.8. These values are symbolic to demonstrate the effect of guard time on throughput.

In this case at the rate of 1 Mbps, the system can transmit 2 Kbits in 2 ms slot duration. In figure 6, we can see the trend of MAC payload with respect to increasing guard time from 1 microsecond (µs) to 1 ms.

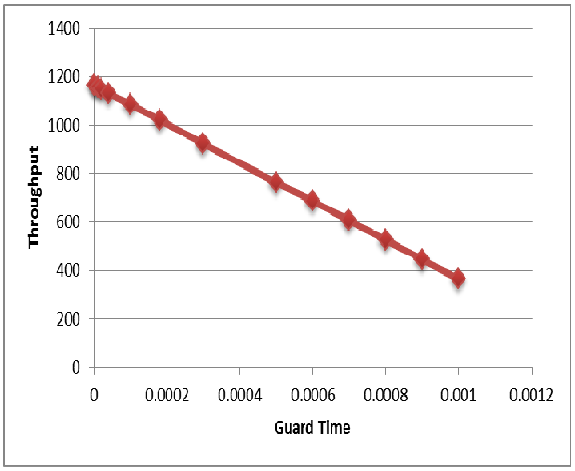

Figure 6: Guard Time vs. MAC Payload

Unlike commercial MANET [13,14], large radio range of tactical waveforms requires large propagation delay margin as shown in figure 7. To optimize the percentage overhead due to guard time, the slot duration should be kept sufficiently large. However, the anti-jamming high hop rate frequency hopping (FH) techniques is also an important requirement of tactical waveforms [15]. Mixing of frequency hopping with TDMA can be done easily, if the FH dwell time is kept equal to TDMA slot time. The higher rate FH leads to the smaller TDMA slot, which in turn creates the bottleneck in terms of overhead of guard time and other packet headers. One possible approach to keep overheads under control is to merge few FH dwells to make a TDMA slot unit. This approach requires providing another guard but of smaller duration compared to propagation time, within TDMA packets at each FH boundary. This guard time counts for frequency tuning and PA ramp up/ PA ramp up down. Moreover, the larger the slot time, physical layer may need to repeat its preamble to keep the receiver synchronized.

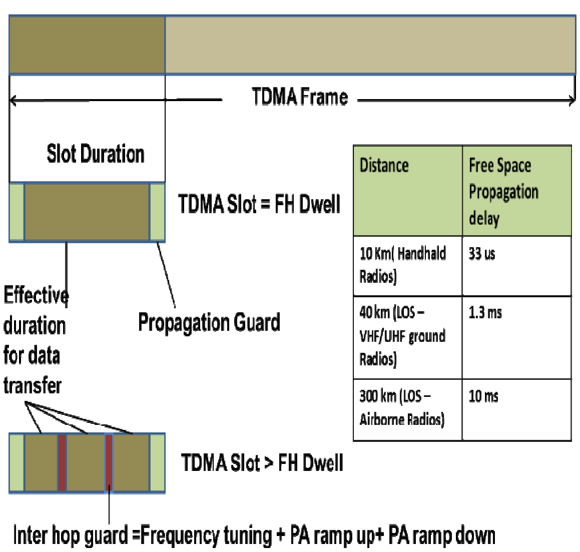

Figure 7: Slot Duration Selection Constrains

To cater for the inter hop guard (I_g) due to FH slot merger the equation (5) gets modified and the value of x is now calculated by equation 7.

$$x = [\{NS - (g + (N-1)I_g)\}R_b - p]F_r - M_H \text{-(7)}$$

Where N is the number of the slot merged. The effect of the slot merger on throughput is presented in figure 8. From the graph it is obvious that the throughput increases with higher number of merged slots. In this case, we have assumed basic slot duration S = 2 ms, guard time g = 200 µs and rest other parameters are same as per previous case. The inter-hop guard (Ig) duration is assumed 50 µs and graph has been plotted for three Rb values 1 Mbps, 1.5 Mbps and 2 Mbps.

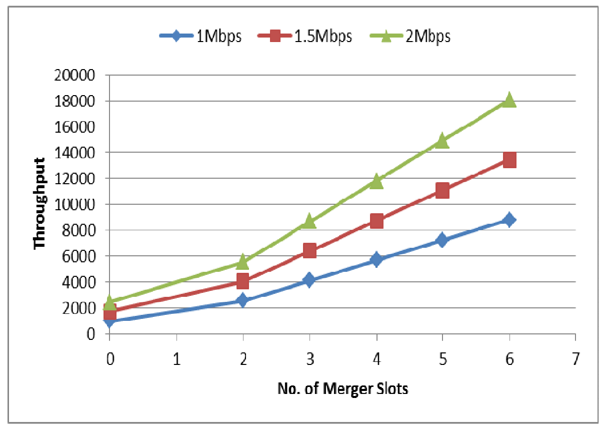

Figure 8: Throughput vs. Number of Merge Slots

IV. CONCLUSION

In the paper various aspects of MAC frame design are presented. The impact of network size and TDMA frame duration on network throughput and channel data rate is formulated. The analytical equation is also developed for MAC throughput for various framing parameters of physical transmit bust. The effect of guard time and slot merging for frequency hopping is also illustrated.Most of the discussed constrains are not much deliberated for commercial ad hoc network due to their short range of operation and less demanding requirements. However, for tactical MANET design, it is essential to consider these constrains and suitability trade-off their value to maximize the network throughput and other performance metrics.

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