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WRED PERFORMANCE ANALYSIS AND DESIGN FOR TACTICAL SATELLITE COMMUNICATION

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ABSTRACT

One of the issues with the use of satellite communications (SATCOM) in tactical networks is the disconnection between the planning and management of the satellite networks and the network operations including planning and management of the deployed tactical network. This paper attempts to bridge this gap, addressing how the router interface connected to a satellite terminal can be configured to optimize the use of the satellite resources.

Tactical networking community stakeholders have suggested the weighted random early detection (WRED) as a means to provide functional capabilities for the military precedence-based assured service (PBAS). This paper argues that WRED configurations is not "one size fits it all", thus derives formulas and procedures to analyze the WRED performances for various configurations. The paper presents a reference WRED design in application to optimizing the tactical SATCOM resources.

For the SATCOM link model given, formulas and procedures to analyze the packet drop and delay characteristics are derived to help engineers to carry out the network performance analyses for various WRED configurations. Impact of packet buffer size on the network performances is investigated to provide a knowledge base for the WRED design. The applicable ranges of the WRED configuration parameters and their impact on performance variations are investigated to help understand and design the WRED. A reference WRED configuration is presented to guide the WRED design for the tactical SATCOM network. The thought process to establish the reference configuration is also given to help understand the reasoning behind the design procedures. The results on packet drop and delay characteristics obtained for various WRED configurations show that the presented analysis method is applicable to the WRED performance analysis and design for the tactical SATCOM.

I. INTRODUCTION

In support of the Global Information Grid (GIG) Quality of Service (QoS) capability, the military PBAS framework and a set of guiding principles have been proposed in [1] to define the functional capabilities to include data services with elastic flows such as TCP. Technical issues related to provide the precedence-based services and the several approaches to support the network capabilities have been discussed in [2], suggesting further investigations on the QoS measures including WRED to favor higher precedence flows. A Markov Chain model of WRED algorithm has been presented in [3], illustrating the performance analysis res*ults*.

The purpose of this paper[1] is to derive formulas and procedures to analyze the WRED performances for various configurations and proposes a reference WRED design in application to the tactical satellite communications. Since the performance measures as well as the performances among the different precedence classes are inter-related, it will not be feasible to establish a simple WRED design procedures. For example, changing one WRED parameter causes the variations in both packet drop and delay characteristics. A change in a WRED parameter for the routine class traffic causes the variations in packet drop and delay characteristics for the priority class traffic. The performances vary also for different traffic profiles. Considering the complexity of the issue, this paper focuses on providing the analysis formulas and procedures clearly, to help engineers to easily carry out the network performance analyses for various WRED configurations. A reference WRED configuration is presented to guide the WRED design for the tactical SATCOM. The process to establish the reference configuration is also given to help understand the reasoning behind the design procedures.

QoS configuration in the IP network basically consists of packet buffers. WRED is configured for a packet buffer, effectively assigning different buffer sizes for the multiple precedence classes. Therefore, as a knowledge base for the WRED design, it is essential to understand the impact of buffer size on the network performances. As seen in [4], [5], and [6], buffer sizing issue has been studied in depth for router buffers in the Internet. Based on the results of those studies and using the performance analysis developed in this paper, the impact of the buffer size on the tactical SATCOM network performances is investigated.

This paper is organized as follows. The SATCOM link model is described in section II. Section III derives formulas and procedures to analyze the network performances of tactical data queue configured using the WRED. The impact of buffer size on the performances is investigated in section IV. Section V describes the WRED design considerations and presents a reference WRED design for tactical the SATCOM. Section VI provides the summary and conclusion.

II. SATCOM LINK MODEL

The SATCOM link model to be investigated in this paper is depicted in Figure 1. The model represents a two-hop SATCOM link between a pair of remote terminals. It consists of TDM forward link and TDMA return link. In consideration of the network performance management and control, this paper considers the network configuration elements including: carrier sizes of the forward and the return links, packet queues configuration, queues bandwidth allocation, and the WRED configurations of the tactical edge and hub networking components.

[1] This paper is based upon work supported by CERDEC S&TCD under Task Order W15P7T-06-D-E407-DO 0023. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsor.

The QoS configuration model for the SATCOM Link is given in Figure 2. It is derived from [2], just adding the data queue to carry network control packets. From the Figure, it is assumed that the bandwidth of each queue including the tactical data queue is configured by the transmission rate, i.e., in Kbps. Radom early detection (RED) parameters, including MinTh, MaxTh, and MaxP, are depicted in Figure 3. For the WRED, those parameters are configured for each and every precedence class packets in the tactical data queue.

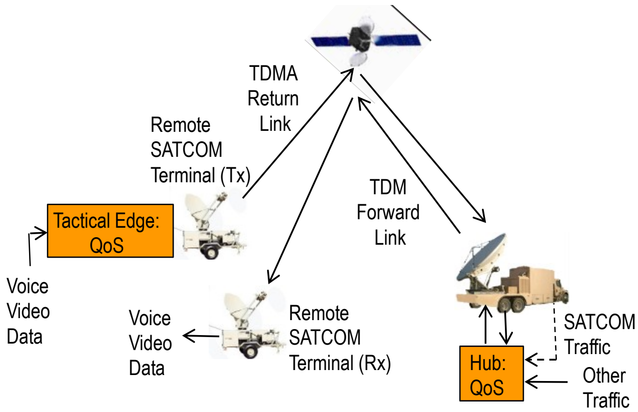

Figure 1: SATCOM Link Model

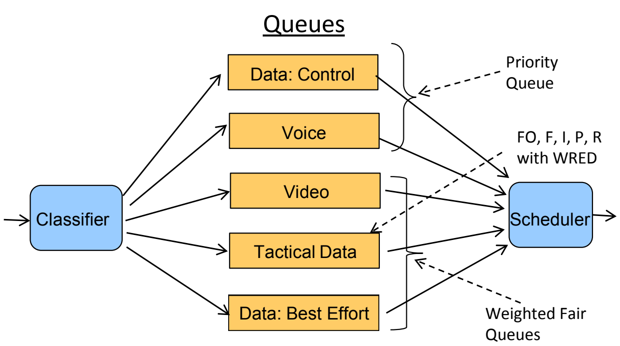

Figure 2: QoS Configuration Model

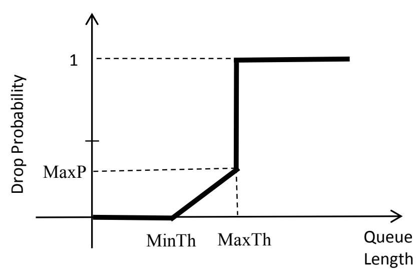

Figure 3: RED Configuration

III. ANALYSIS OF COVERAGE OVERLAP

This section derives formulas and procedures to analyze the packet drop and delay characteristics in accordance with the QoS configurations at the tactical edge and the hub. This analysis is refined and expanded based on the methodology given in [3] and [7]. Here, the packet queue is modeled following the Continuous Time Markov Chain, as depicted in

Figure 4. From the Figure, the symbols are denoted as follows:

- S_i : State of queue length of i
- μ : Service rate
- D_i : Dropped rate at state i
- Q_i : Queued rate at state i
- N : Maximum queue length, or queue buffer size

Then, the state transition probability $P(i,k)$, i.e., probability of S_i to S_k transition, can be given by:

If $i = 0$: $P(0,1) = Q_0/(Q_0+\mu)$, $P(0,0) = \mu/(Q_0+\mu)$

else if $i = N$: $P(N,N) = D_N/(D_N+\mu)$,

$P(N,N-1) = \mu/(D_N+\mu)$

else: $P(i,i+1) = Q_i/(Q_i+D_i+\mu)$: queued

$P(i,i) = D_i/(Q_i+D_i+\mu)$: dropped

$P(i,i-1) = \mu/(Q_i+D_i+\mu)$: served

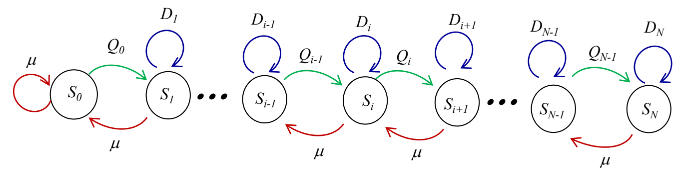

Figure 4: Continuous Time Markov Chain Model

If we define the following denotation;

T_M : State transition rate for instance M

μ : Service rate

λ_j : Arrival rate of precedence class j packet

x: Instantaneous queue length

$MinTh_j$, $MaxTh_j$, $MaxP_j$: WRED parameters for precedence or MLPP class j packet,

following the packet handling process of the WRED, the state transition rate can be given for each instance as follows:

1. $x \le MinTh_j$: queued $T_1 = \lambda_j$,
2. $\mathrm{MinTh_j} < \mathrm{x} \le \mathrm{MaxTh_j}$: dropped

   $T_2 = \lambda_j \cdot MaxP_j \cdot (x - MinTh_j)/(MaxTh_j - MinTh_j)$
3. $MinTh_j < x \le MaxTh_j$: queued

   $T_3 = \lambda_j \cdot (1 - MaxP_j \cdot (x - MinTh_j)/(MaxTh_j - MinTh_j))$
4. $x > MaxTh_j$: dropped $T_4 = \lambda_j$
5. $x > 0$: queue reduced $T_5 = \mu$

Then, the state transition probability $P_j(i,k)$ for MLPP class j, can be given by:

If $x = 0$: $P_j(0,1) = \lambda_j/(\lambda_j+\mu)$, $P_j(0,0) = \mu/(\lambda_j+\mu)$

else if $x = N$: $P_j(N,N) = \lambda_j/(\lambda_j+\mu)$, $P_j(N,N-1) = \mu/(\lambda_j+\mu)$

else if $0 < x \le MinTh_j$:

$P_j(i,i+1) = T_1/(T_1+T_5) = \lambda_j/(\lambda_j+\mu)$, $P_j(i,i) = 0$,

$P_j(i,i-1) = T_5/(T_1+T_5) = \mu/(\lambda_j+\mu)$

else if $MinTh_j < x \le MaxTh_j$:

$P_j(i,i+1) = T_3/(T_2+T_3+T_5)$

$P_j(i,i) = T_2/(T_2+T_3+T_5)$

$P_j(i,i-1) = T_5/(T_2+T_3+T_5)$

else $MaxTh_j < x < N$:

$P_j(i,i) = T_4/(T_4+T_5) = \lambda_j/(\lambda_j+\mu)$

$P_j(i,i-1) = T_5/(T_4+T_5) = \mu/(\lambda_j+\mu)$

Using the formula given in [8], stationary probability of state i, $Ps(i)$, or the vector $\boldsymbol{Ps}$, is obtained by,

$$\boldsymbol{Ps} = \boldsymbol{b}\,(\boldsymbol{P} - \boldsymbol{I})^{-1}$$

where $\boldsymbol{b}$ denotes a row vector with 1 in the first entry and zeros elsewhere, $\boldsymbol{P}$ denotes the state transition matrix, and $\boldsymbol{I}$ denotes an identity matrix. $Ps(i)$ represents the probability distribution of the queue length, or subsequently the probability distribution of the packet delay since the waiting time of the packet in the queue is proportional to the queue length once the queue service bandwidth is given. Finally, the queue dropping rate for MLPP class j, Pd_j, is obtained by:

$$Pd_j = Ps(1) * P_j(1,1) + Ps(2) * P_j(2,2) + \cdots + Ps(N) * P_j(N,N)$$

IV. IMPACT OF BUFFER SIZE ON NETWORK PERFORMANCE

For the network QoS control, WRED is configured in the packet queue buffers at the hub and remote SATCOM transmission links as shown in Figure 1 and Figure 2. The impact of such a buffer on the network performance is a fundamental element to be investigated for understanding and designing the WRED. This section investigates the impact of buffer size on the packet drop and queuing delay characteristics, as a knowledge base for the networking technology development concerning the WRED.

One of the primary purposes of packet buffer in the network QoS control is to reduce the frequency of packet drops by absorbing the transient bursts at packet network nodes. In general, packet drop probability becomes lower as the buffer size grows larger. However, as the buffer size grows, the packet transfer delay can be increased at the transient packet bursts. Larger buffer also demands larger memory and more processing power. For the tactical SATCOM networks, memory size and processing power are not a concern practically due to relatively the low data rate of the SATCOM links. [They can typically be a concern for high-data-rate terrestrial Internet backbone links.] Therefore, the packet drop and delay performances are of concerns in the analysis. In general, one would like to set the buffer size in such a way that it is large enough to sufficiently reduce the packet drop rate but not too large to generate significant delay.

<u>Packet Drop</u>

Using the formulas derived in section III, the analytical results on the packet drop probability due to buffer overflow, or the buffer tail drop probability, versus buffer size are illustrated in Figure 5, where μ and λ denote the service rate and the arrival rate, respectively. In network QoS configuration, the service rate and the arrival rate are given in terms of packets per second. For a steady flow of packets in a same length, they will be proportional to the transmission bandwidth for the queue buffer and the incoming traffic rate, respectively. The results are obtained as a special case of the queue drop analysis method given in section III, i.e., setting all of the WRED parameters (in reference to Figure 3) MinTh and MaxTh by the buffer size. The lower left corner of Figure 5 is zoomed-in in Figure 6.

From Figure 5, one can note that for the normalized service rate μ/λ of less than or equal to around 0.95, i.e., for the case that incoming traffic exceeds the transmission bandwidth of the queue, the packet drop rate does not go below a certain level despite of a big buffer size. It is due to the fact that the queue continuously builds up and remains close to any given buffer size, for such a case. On the other hand, for μ/λ of greater than 1.05, i.e., for the case that the incoming traffic is smaller than the transmission bandwidth of the queue, the packet drop rate reduces quickly as the buffer size grows.

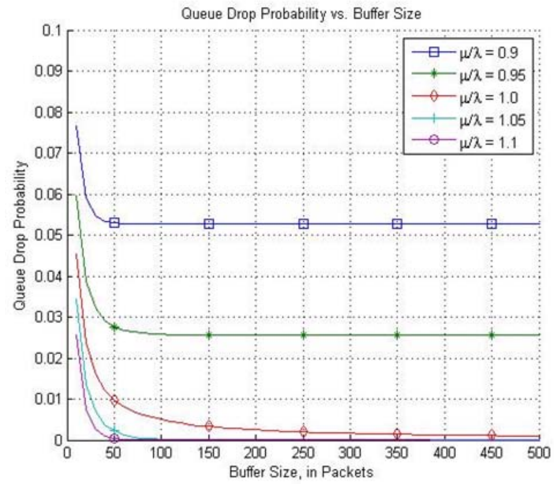

Figure 5: Buffer Tail Drop Probability versus Buffer Size

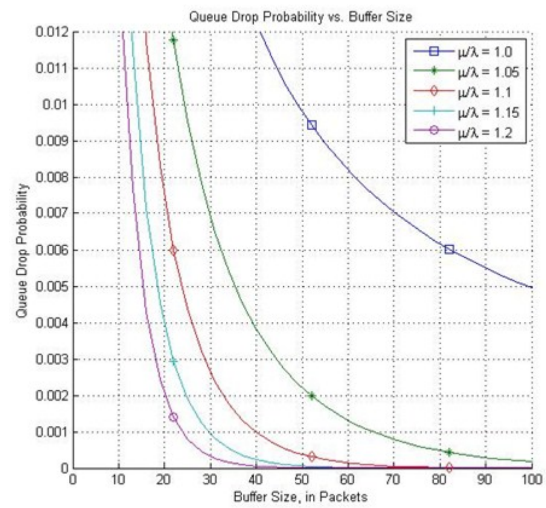

Figure 6: Buffer Tail Drop Probability versus Buffer Size (Zooming in the area of small buffer sizes)

Analysis results such as Figure 6 can provide a reference for setting a buffer size in network QoS configuration. For example, for μ/λ of 1.1, i.e., for the queue transmission bandwidth of 1.1 times the incoming traffic rate, buffer size of 40 will result in packet drop rate of about $1\text{x}10^{-3}$ and that of 60 will result in packet drop rate of about $1\text{x}10^{-4}$.

<u>Queuing Delay</u>

It is intuitive that the maximum queuing delay can be controlled by adjusting the buffer size. However, considering that propagation delay (which is inevitable for SATCOM) for a two-hop SATCOM transmission such as remote-to-hub-to-remote link is typically an order of 500 ms, we also would like to know how much delay is caused by the buffer, practically in comparison with the propagation delay. Precisely, assuming that the packet arrival event is represented by a probabilistic model [In fact, the same assumption applies throughout the analysis.], this section analyzes the probability distribution of the delay.

The analytical results on cumulative probability of queuing delay for carrier data rate[2] of 4 Mbps are illustrated in Figure 7. The results are obtained as a special case of the queuing delay analysis method given in section III, i.e., setting all of the WRED parameters (in reference to Figure 3) MinTh and MaxTh by the buffer size. From Figure 7, it is noted that the delay characteristics significantly changes when μ/λ changes from 0.95 to 1.05. It means that small traffic change at the vicinity of the queue transmission bandwidth significantly affects the queuing delay. Also noted is that at the carrier data rate of 4 Mbps, the amount of delay for μ/λ of 1.1 is much smaller than the propagation delay of a SATCOM link. Since the delay is inversely proportional to the carrier data rate, one can expect that the delay could become a concern as the carrier data rate becomes lower.

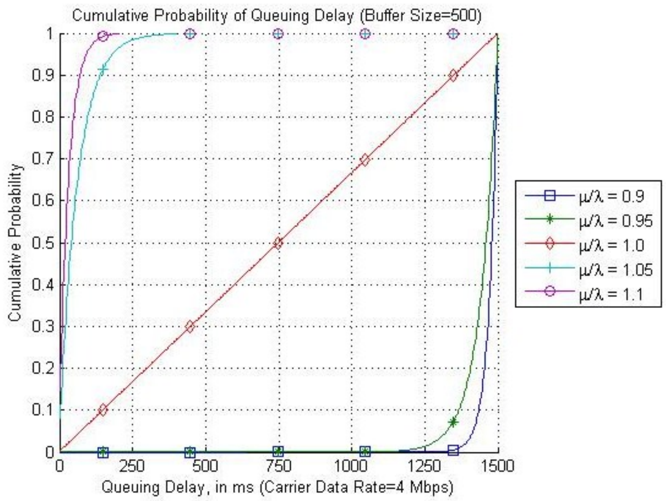

Figure 7: Cumulative Probability of Queuing Delay

It should be noted that for a certain μ/λ, the delay estimated in time is inversely proportional to the transmission rate of the SATCOM carrier. It implies that the delay is larger at a remote than that at the SATCOM hub, considering that the remote-to-hub or the return link carrier data rate is typically much lower than the hub-to-remote or the forward link carrier data rate. Also noted is that one can estimate the queuing delay distribution for other carrier data rates by multiplying the queuing delay by 4/(carrier data rate in Mbps), with reference to Figure 7.

V. WRED CONFIGURATION FOR TACTICAL SATCOM

Considering the complicated associations among the WRED configuration parameters and network performance characteristics, it will not be feasible to establish a simple WRED design procedure. To help understand and design the WRED, this section investigates the applicable ranges of the WRED configuration parameters and their impact on the performance variations.

From Figure 3, MinTh is a parameter to be determined firstly, based on the deliberations given in the impact of buffer size. In the original RED design concept, the slope between MinTh and MaxTh is to prevent synchronization among the multiple TCP flows, by randomizing the packet drop among the flows. Here, it will work for TCP flows of each precedence. MaxP is typically given by an order of 0.1 as it is known that only a little randomization is necessary to prevent such synchronization.

[2] Here we consider the data rate in IP layer, or the data rate applied to the packet transmission.

Strict Drop Policy versus Overlapping Drop Policy

For tactical networking, class-based WRED scheme is used to implement the precedence-based quality control. An illustration of WRED configuration is shown in Figure 8, (which represents a "strict drop policy" referred in [2],) where packets of a lower precedence drop before those of a higher precedence drop, as the queue length increases.

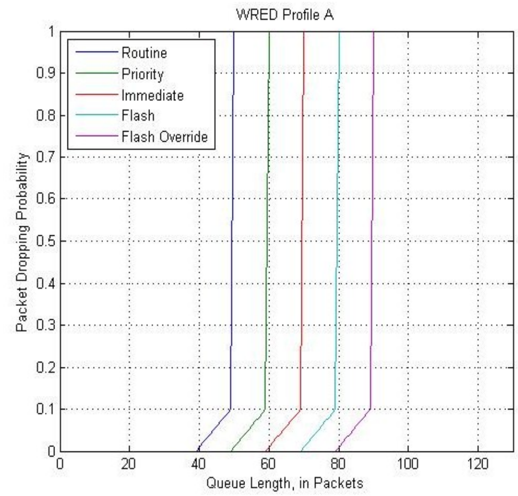

Figure 8: WRED Profile-A

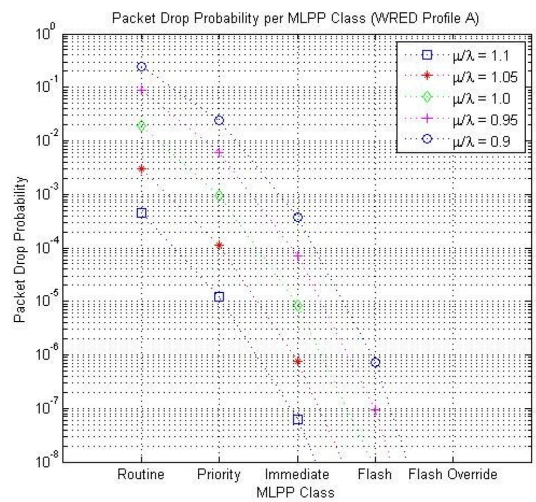

Figure 9: Packet Drop Probability (WRED Profile A)

The analysis results of the packet drop probability for the WRED Profile-A is given in Figure 9. In the analysis, the arrival rate of the traffic for each precedence level is given by 0.2 x (total traffic), equally for all precedence levels. From Figure 9, it is noted that the packet drop probability for the higher precedence levels are very low even for the case that the normalized service rate is as low as 0.9. This is due to the fact that the amount of traffic brought to the queue is reduced as all of the lower precedence packets are dropped. In practice, such a low packet drop probability would be meaningless, since the packet drop due to other causes such as transmission error would be larger than that. Therefore, as a result of this study, we would recommend something like WRED Profile-B shown in Figure 10, (which represents an "overlapping drop policy" referred in [2],) where the slopes between MinTh's and MaxTh's overlap, for example, MaxTh for the routine level is larger than MinTh for the priority level. The analysis results of the packet drop probability for the WRED Profile-B is given in Figure 11. Comparing the results in Figure 11 with those in Figure 9, it is noted that the packet drop probability for the lower precedence levels becomes lower, while that for the higher precedence levels becomes higher. However, considering the packet drop due to other causes, the drop probability for the higher levels is sufficiently low in a practical sense, considering the packet drop due to other causes.

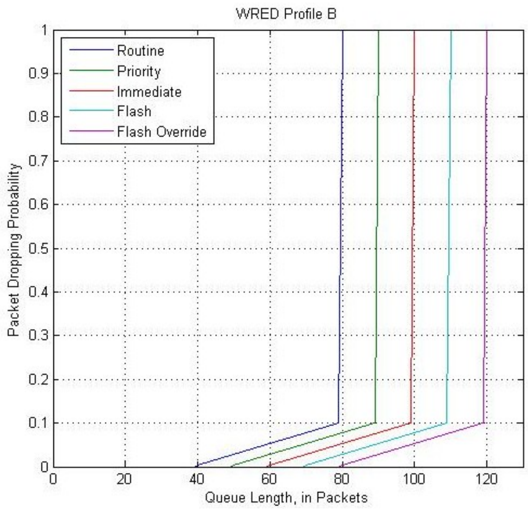

Figure 10: WRED Profile-B

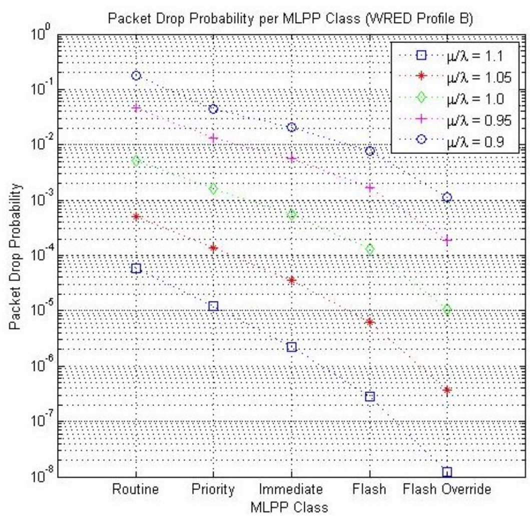

Figure 11: Packet Drop Probability (WRED Profile B)

Reference WRED Configuration for Tactical Data Queue

Based on the findings obtained by extensive analysis results for a wide range of configuration parameters (although only shown selected results in this paper), the following procedure is suggested for configuring the WRED parameters of the tactical data queue for the SATCOM network operation:

For the WRED Configuration at a Remote Terminal:

1. Set a target packet drop probability for the routine class of the traffic at the remote SATCOM terminal. The probability is determined by considering the maximum packet drop rate in the SATCOM link, or by the requirement if given. A default value of 1×10^{-3} is suggested.
2. MinTh of the routine class is set to satisfy the target packet drop probability for μ/λ of 1.1.
3. MinTh's of the priority, immediate, flash, and flash override classes are respectively set by adding 10, 20, 30, and 40 to the MinTh of the routine class.
4. For all precedence classes, MaxTh of each class is set by adding 40 to the MinTh of each corresponding precedence class.
5. For all precedence classes, MaxP's of all classes are set by 0.1.

For the WRED Configuration at the Hub:

1. Set a target packet drop probability for the routine class of the traffic at the hub by 1/10 of that at the Remote SATCOM terminal.
2. Perform the same procedure steps 2-5 as for the remote SATCOM terminal.

The suggested procedure is not meant to be a solid one to observe, rather it could be a starting point for further evaluation and modification. Modification of the configuration parameters will result in a delicate variation in the network performance characteristics. There might not be simple better or worse configurations.

Reasoning for each step for the remote is explained as follows:

1. Since the packet drop probability of the higher precedence traffic is typically far less than that of the routine traffic, we can plan the packet drop rate of the network in accordance with the operational requirement in this way.
2. Based on the observations made on the packet drop performances for various μ/λvalues, μ/λ of 1.1 seems to be a reasonable value for the planning.
3. It is observed that a small difference in the MinTh values between different precedence classes makes significant difference in the packet drop characteristics. Therefore the difference between the precedence classes needs to be small. Theoretically, it could be as small as one. However, considering the random nature of the traffic (For example, there would be a duration when the traffic consists of only one precedence class.), it is suggested by 10.
4. It is observed that it would be appropriate that the slopes part of the WRED characteristics overlap with other precedence classes. The (MaxTh – MinTh) value of 40 gives ¾ overlap of the slopes part with an adjacent precedence class.
5. In principle, the slope part is to prevent so called "TCP Synchronization", which lowers the link utilization. It is known that a slight randomization or the small value of MaxP is sufficient for the purpose. So we pick an order smaller value to 1.

Since the carrier data rate and the queue bandwidth of the hub link is much higher than those of the remote, it is feasible to set hub WRED parameters in such a way that the packet drop rate is lower than that of the remote and the queuing delay is smaller than that of the remote. Starting from setting the target packet drop probability for the routine class by 1/10 of that of the remote, such an objective would be achievable.

Based on the procedure given in the previous section, the WRED parameters are obtained as shown in Table 1. In the Table, the default value of 1×10^{-3} is selected for the target packet drop probability for the routine class of the traffic at the remote SATCOM terminal. Then, based on the analysis results given in Figure 6, MinTh of 40 is obtained for the routine class. For the hub, after setting the target packet drop probability for the routine class by 1×10^{-4}, MinTh of 60 is also obtained for the routine class based on the analysis results given in Figure 6.

Table 1: WRED Parameters (Reference Configuration)

Precedence	Remote SATCOM Terminal			Hub		
	MinTh	MaxTh	MaxP	MinTh	MaxTh	MaxP
Routine	40	80	0.1	60	100	0.1
Priority	50	90	0.1	70	110	0.1
Immediate	60	100	0.1	80	120	0.1
Flash	70	110	0.1	90	130	0.1
Flash Override	80	120	0.1	100	140	0.1

For a two-hop (remote-to-hub-to-remote) SATCOM link, Figure 12 shows analysis results for the end-to-end packer loss probability, which additionally accounts the effect of the forward and the return links packet transmission error to the combined effects.

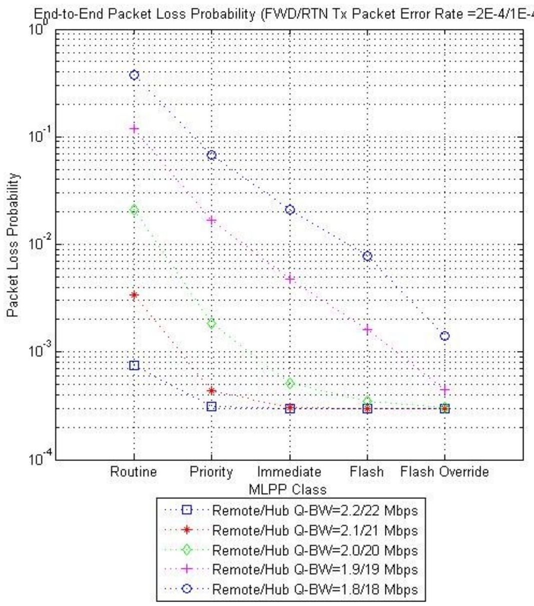

Figure 12: End-to-End Packet Loss Probability

The analysis results for queuing delay are illustrated in Figure 13 for μ/λ values of 0.9, or equivalently, for remote/hub queue bandwidth of 1.8/18 Mbps with remote/hub traffic of 2.0/20 Mbps. From the Figure, it is noted that the remote link generates much more delays than the hub link does, although the buffer length of the remote is shorter than that of the hub. That is because the carrier data rate of the remote is 1/10 of that of the hub in the illustration.

VI. SUMMARY AND CONCLUSION

This paper analyzes the WRED performances and presents a reference WRED design in application to the tactical SATCOM network. For the SATCOM link model given, formulas and procedures to analyze the packet drop and delay characteristics are derived to help engineers to carry out the network performance analyses for various WRED configurations. Impact of packet buffer size on the network performances is investigated to provide a knowledge base for the WRED design. The applicable ranges of the WRED configuration parameters and their impact on performance variations are investigated to help understand and design the WRED. A reference WRED configuration is presented to guide the WRED design for the tactical SATCOM network. The thought process to establish the reference configuration is also given to help understand the reasoning behind the design procedures. The results on packet drop and delay characteristics obtained for various WRED configurations show that the presented analysis method is applicable to the WRED performance analysis and design for the tactical SATCOM.

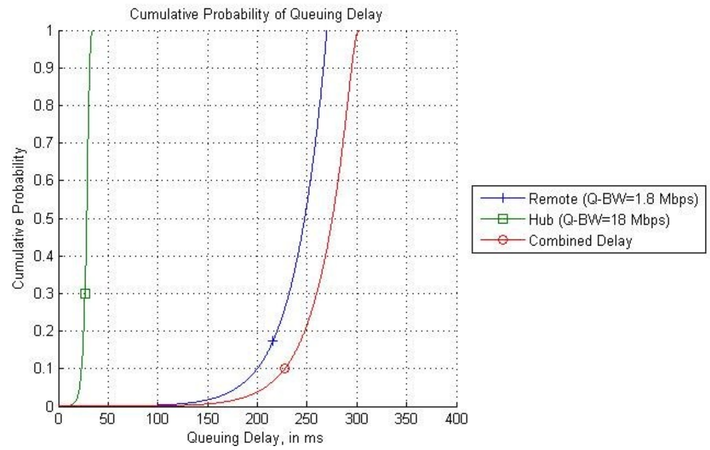

Figure 13: Results of Queuing Delay Analysis

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