Ka-Band Link Optimization with Rate Adaptation

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***Abstract*— On-going development of Ka-band capability for the Deep Space Networks (DSN) will radically increase the bandwidth available to support advanced mission concepts envisioned for future robotic as well as human exploration of Mars and beyond. While Ka-band links can operate at much higher data rate than X-band, they are much more susceptible to fluctuating weather conditions and manifest a significant trade-off between throughput and availability. If the operating point is fixed, the maximum average throughput for deep space Ka-band link is achieved at about 80 percent availability, i.e., weather-related outages will occur about 20 percent of the time. Low availability increases the complexity of space mission operation, while higher availability would require additional link margins that lowers the overall throughput. To improve this fundamental throughput-availability tradeoff, data rate adaptation based on real-time observation of the channel condition is necessary.**

In this paper, we model the ka-band channel using a Markov process to capture the impact of the temporal correlation in weather conditions. We then develop a rate adaptation algorithm to optimize the data rate based on real time feedback on the measured channel conditions. Our algorithm achieves both higher throughput and link availability as compared to the constant rate scheme presently in use.

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1. INTRODUCTION

Ka-band transmission is viewed as a primary means for meeting the increasing demands for high data rate services of space exploration missions. Due to the increase in antenna gains at higher frequencies, an improvement in the signal strength by a factor of four can be expected in the transition from X-band to Ka-band [1]. Moreover, at Ka-band, deep space communications is allocated 500 MHz of bandwidth compare to the 50 MHz of bandwidth allocated to the X-band [1]; leading to even greater increase in throughput when using Ka-band.

Although the throughput gain in Ka-band can be significant, Ka-band data transmission is susceptible to weather fluctuations. The deep space systems use receivers with very low noise temperatures of approximately 25 K. This makes them extremely sensitive to atmospheric effects [2]. Weather events, such as rain and clouds, increase the moisture in the atmosphere; and consequently the noise temperature.

The proposed data transmission scheme in Ka-band, which is going to be demonstrated on the Mars Reconnaissance Orbiter (MRO), uses constant rate transmission. Specifically, during a particular communication session, based on the statistics of the atmospheric noise temperature and pass geometry, a link configuration is decided in advance to achieve a constant transmission rate. When the actual transmission takes place, the targeted data rate can be achieved with acceptable reliability if the atmospheric noise temperature is below a certain threshold noise temperature. If the noise temperature exceeds the threshold, significant data corruption and loss of synchronization will occur, making the link unusable.

An immediate consequence of using a pre-determined, fixed rate transmission scheme is the disruption of data continuity due to bad weather. Weather phenomena such as microbursts can significantly increase the system noise temperature thus causing outages for a short period of time [1]. If a timely decision on whether to retransmit the lost data cannot be made, such disruptions will greatly complicate mission operations. In order to ensure the reliability of a communication link, additional power margin will be added to combat the weather fluctuation, at the expense of link throughput.

In this paper we propose to use an adaptive rate transmission scheme to combat the weather effect associated with the Ka-band link while maintaining data continuity and high throughput. Specifically, our adaptive rate transmission scheme predicts the channel conditions (i.e., the atmospheric noise temperature) based on the current and past noise temperature observations. A transmission rate is then chosen after adding an appropriate margin to the predicted link budget. This additional power margin is essential to mitigate any prediction errors. The transmitter adapts its transmission rate at regular intervals of relatively short duration (e.g., 5 minutes). If the predicted noise temperature plus margin is higher than the actual noise temperature during the interval, data can be successfully transmitted at the chosen data rate.

Using the atmospheric noise temperature collected at the Deep Space Network Madrid cite for 1678 days, we compare the performance of the constant rate transmission (CRT) scheme and the adaptive rate transmission (ART) scheme in terms of data availability (continuity) and throughput. For the constant rate transmission scheme, the maximum throughput is achieved with a temperature threshold of 16 K; which also yields 80 percent availability. In contrast, as shown in Fig.1 the adaptive rate scheme achieves 40 percent greater throughput for the same (80 percent) level of availability. A similar comparison, at different availability levels, is also shown in the figure. For example, at 99 percent data availability, the throughput of the ART scheme is more than four times that of the CRT scheme.

For clarity of presentation, we have excluded the deterministic variation of spacecraft elevation angle from our analytic model because its impact can be overcome by pre-scheduled adjustments to the transmit power or data rate. These adjustments to deterministic fluctuations can be easily handled by both the ART and CRT schemes. Of course, such adjustments do not take into account the stochastic fluctuations due to weather effects. Hence the focus of the ART scheme is to adapt the data rate to stochastic fluctuations in the noise temperature.

The rest of this paper is organized as follows: Section 2 describes the Ka-band link margin and the atmospheric noise measurement data. The details of the constant rate transmission scheme and adaptive rate transmission scheme are presented in section 3. Section 4 describes the prediction algorithm and the algorithm for choosing the adaptive margin in the ART scheme. Finally, section 5 compares the CRT scheme with the ART scheme in terms of throughput performance and link availability.

2. Link margin analysis

The standard link equation that relates the transmission rate to the required Signal to Noise Ratio (SNR) per bit is given by,

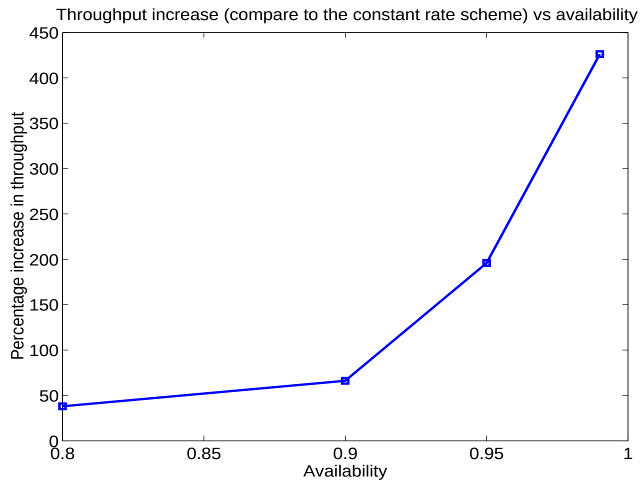

Fig. 1. Comparison of CRT scheme and ART scheme in terms of the percentage throughput increase and availability of data.

$$\frac{P_r}{N_0} = R(\frac{\mathcal{E}_b}{N_0})_{req}. \tag{1}$$

The received SNR on the ground, P_r/N_0, is given by,

$$\begin{aligned}\frac{P_r}{N_0} =&P_{Amp} \cdot \epsilon_{Amp} \cdot \frac{4\pi^2 r_{sc}^2}{\lambda_2} \cdot \epsilon_{sc} \cdot L_{psc}^{-1} \cdot (\frac{\lambda}{d})^2 \\ &\cdot L_{Atm}^{-1} \cdot L_{pg}^{-1} \cdot \frac{4\pi^2 r_G^2}{\lambda^2} \cdot \epsilon_G \cdot (k \cdot T_{sys})^{-1}\end{aligned} \tag{2}$$

In the above equation, P_{Amp} is the power into the spacecraft amplifier; ϵ_{Amp} is the amplifier efficiency; λ is the RF wavelength; r_{sc} and r_G are spacecraft and ground antenna radii, respectively; L_{psc} and L_{pg} are the spacecraft and ground pointing losses, respectively; ϵ_{sc} and ϵ_G are the spacecraft and ground antenna efficiencies, respectively; and d is the distance between the spacecraft and the Earth. L_{Atm} is the loss due to atmospheric absorption; T_{sys} is the ground system noise temperature; and k is Boltzman's constant [3]. Both L_{Atm} and T_{sys} are related to the atmospheric noise temperature, T_{atm}. Specifically, the atmospheric loss L_{Atm} is related to T_{atm} through the following approximation [3],

$$L_{Atm} \approx \begin{cases} \frac{275}{275-T_{atm}} & T_{atm} < 275 \\ \infty & \text{otherwise} \end{cases} \tag{3}$$

The system noise temperature, T_{sys}, reflects how noisy the system is. It consists of equipment noise temperature, atmospheric noise temperature, and observed cosmic background noise. That is,

$$T_{sys} = T_{eq} + T_{atm} + \frac{2.7}{L_{Atm}} \tag{4}$$

To illustrate the relationship between weather (i.e., T_{sys}) and the transmission rate, we have:

$$R = \frac{\alpha}{T_{eq} + T_{atm} + \frac{2.7}{L_{Atm}}} \frac{275 - T_{atm}}{275} / (\frac{\mathcal{E}_b}{N_0})_{req} \tag{5}$$

where α encapsulates the rest of the terms in Eq.(2). For a transmission at rate R to be successful, we must have

$$\frac{\alpha}{T_{eq}+T_{atm}+\frac{2.7}{L_{Atm}}}\frac{275-T_{atm}}{275}/R \geq (\frac{\mathcal{E}_b}{N_0})_{req} \quad (6)$$

In the constant rate transmission scheme, a transmission rate and the required SNR per bit are selected first. If the actual SNR per bit at the receiver side is greater than the required SNR per bit, the transmission will be successful. Based on the weather statistics, one can select a rate such that transmissions are successful a certain percentage of the time. For the constant rate transmission scheme, there is a tradeoff between the transmission rate and the link availability. Using a higher data rate, requires lower noise temperature; and that occurs with lower probability. Using the adaptive rate transmission scheme, the atmospheric noise temperature in the future is predicted first. More specifically, if the current time is t, it is necessary to predict the atmospheric noise temperature at time $t+L$, where L is at least the signal propagation time from the ground to the spacecraft and back (i.e., one round trip time). In the case of the Mars Reconnaissance Orbiter, the round trip time is usually between 20 to 30 minutes. Given the predicted atmospheric noise temperature and the required SNR, a projected transmission rate can be obtained. A transmission at a certain projected rate is successful only if the actual received SNR is greater than the required SNR. In order for this adaptive rate transmission scheme to work properly, it is necessary to combat the prediction error. By adding a margin Δ to the predicted atmospheric noise temperature, one can decrease the probability that the actual received SNR is smaller than the required SNR, hence, assuring higher link availability. As we will see later, the way in which the margin Δ is chosen will have a significant impact on the performance of the adaptive transmission scheme.

The atmospheric noise temperature data used in this paper is measured at Deep Space Communications Complex 60 (Madrid) using a water vapor radiometer (WVR) over 1678 days. The temperature data were gathered at the rate of one measurement every five minutes. Fig. 2 shows the cumulative distribution function of T_{atm}. It can be seen from the figure that for 80 percent of the time the noise temperature is below 16 K; similarly for 85, 90, and 99 percent availability, the atmospheric noise temperature are below 22 K, 41.5 K, and 89.3 K respectively.

3. Throughput and Link Availability

To get the throughput performance of the constant rate transmission scheme using the measured noise temperature data, we first calibrate our link model with a baseline design by selecting a threshold atmospheric noise temperature T_0 and the required SNR per bit for link availability. Hence the transmission rate at the noise temperature threshold, $R_c(T_0)$, is given by,

$$R_c(T_0)=\frac{\alpha}{T_{eq}+T_0+\frac{2.7}{L_{Atm}}}\frac{275-T_0}{275}/(\frac{\mathcal{E}_b}{N_0})_{req} \quad (7)$$

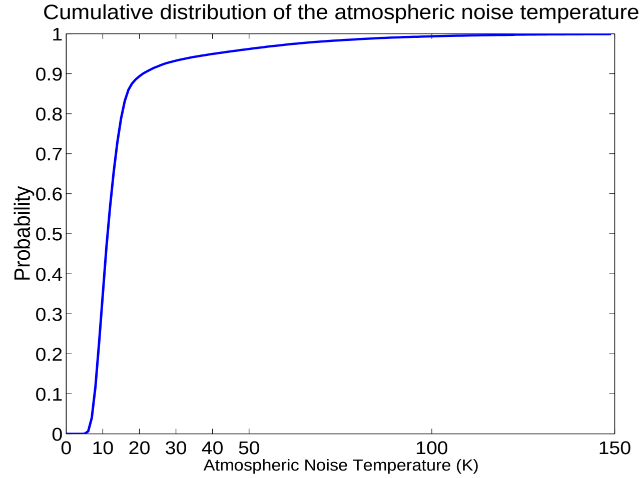

Fig. 2. The cumulative distribution function of T_{atm}.

Let N denote the total number of data measurements and $T(i)$ denote the ith atmospheric noise temperature measurement. The average transmission rate $\bar{R}_c$ with a threshold temperature T_0 can be written as follows,

$$\bar{R}_c(T_0)=\frac{1}{N}\sum_{i=1}^{N}R_c(T_0)\cdot\mathbf{1}_{T(i)<T_0} \quad (8)$$

where

$$\mathbf{1}_{T(i)<T_0}=\begin{cases}1 & \text{if } T(i)<T_0\\ 0 & \text{otherwise}\end{cases} \quad (9)$$

The other performance metric that we are interested is link availability, denoted here as $A(T_0)$, and given by,

$$A(T_0)=\frac{1}{N}\sum_{i=1}^{N}\mathbf{1}_{T(i)<T_0} \quad (10)$$

In general the average transmission rate is a concave function of the reference temperature T_0. When T_0 is low, the average data rate is low due to frequent outages. However, if T_0 is high, the link availability increases but the required SNR per bit forces low data rate transmission. So it is clear for a fixed rate scheme, there is a tradeoff between availability and throughput. From the atmospheric noise temperature data, the maximum $\bar{R}_c$ is achieved when $T_0=16$ K. The link availability, given $T_0=16$ K, is about 80 percent. For 20 percent of the time, the link will not be available for reliable communications. Moreover, since the time scale for weather event is typically long (e.g., minutes to hours); the outage period presents a significant operational challenge to missions that desire constant monitoring/control of remote spacecrafts.

Using an adaptive rate transmission scheme, intuitively, the tradeoff between throughput and availability can be eliminated to a great extent. By setting a new threshold for each time interval (five minutes interval is used in this paper), the adaptive scheme can have both good throughput when channel quality is good and good availability performance when the weather condition is poor. Specifically, at time t, the adaptive rate transmission scheme predicts the atmospheric noise temperature at time $t+t_0$, denoted as $T_p(t+t_0)$, where t_0 is at least one round trip time from the ground to the spacecraft. To mitigate the effect of the prediction error, a small margin Δ is also added to $T_p(t+t_0)$. Based on $\hat{T}(t+t_0) = T_p(t+t_0) + \Delta$, the projected rate of transmission at time $t+t_0$, denoted as $R_p(t+t_0)$, is obtained as follows:

$$R_p(t+t_0) = \frac{\alpha}{g(\hat{T}(t+t_0))} / (\frac{\mathcal{E}_b}{N_0})_{req} \qquad (11)$$

where

$$g(x) = (T_{eq} + x + 2.7 \cdot \frac{275-x}{275}) \cdot \frac{275}{275-x} \qquad (12)$$

When the actual transmitted signal reaches the ground receiver at time $t+t_0$, the actual SNR per bit is given by:

$$SNR(t+t_0) = \frac{\alpha/g(T(t+t_0))}{R_p(t+t_0)} \qquad (13)$$

$$= \frac{g(\hat{T}(t+t_0))}{g(T(t+t_0))} \cdot (\frac{\mathcal{E}_b}{N_0})_{req} \qquad (14)$$

If $SNR(t+t_0)$ is greater than $(\frac{\mathcal{E}_b}{N_0})_{req}$, the transmission is successful. The average throughput of the adaptive rate transmission scheme can be written as:

$$\bar{R}_a = \frac{1}{N-t_0} \sum_{t=1}^{N-t_0} R_p(t+t_0) \cdot \mathbf{1}_{\{SNR(t+t_0) > (\frac{\mathcal{E}_b}{N_0})_{req}\}} \qquad (15)$$

Similarly, the availability of transmissions using the adaptive rate transmission scheme, denoted here as $A_a(T_0)$, is given by:

$$A_a = \frac{1}{N-t_0} \sum_{t=1}^{N-t_0} \mathbf{1}_{\{SNR(t+t_0) > (\frac{\mathcal{E}_b}{N_0})_{req}\}} \qquad (16)$$

4. Adaptive Rate Transmission Scheme: Prediction and Margin

A. *Atmospheric noise temperature prediction*

To predict the atmospheric noise temperature one round trip time ahead, we first investigate the correlations between the atmospheric noise temperature measurements. Fig.3 plots the autocorrelation function of the noise samples. The correlation between samples decreases as the time between samples increases. Now consider a first order autoregressive process described by the following equation:

$$y(t) = a_1 \cdot y(t-1) + w(t) \qquad (17)$$

where $y(t)$ denotes the atmospheric noise temperature measurement at time t, a_1 is a constant, and $w(t)$ denotes the random fluctuation of the temperature at time t independent of $w(s)$ for all $s < t$. Its autocorrelation function is defined as:

$$R(k) = E[y(t) \cdot y(t-k)]$$

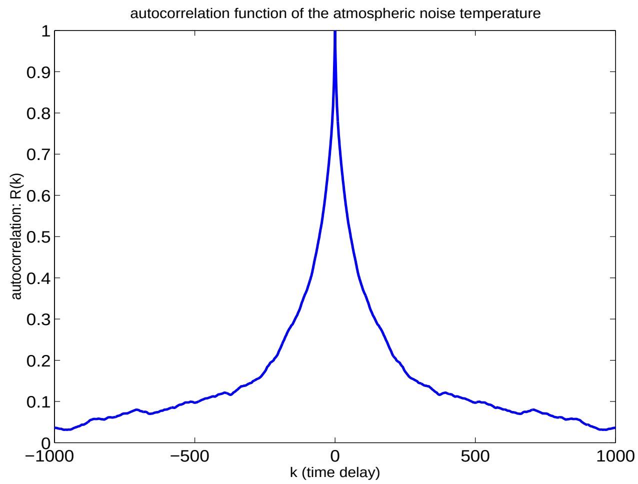

Fig. 3. The autocorrelation function of the atmospheric noise temperature data.

From Eq.(17), a recursive form of the autocorrelation function can be written as the following:

$$R(k) = a_1 \cdot R(k-1) \quad k > 0 \qquad (18)$$

Solving the above equation, we have

$$R(k) = a_1^k \quad k \geq 0$$

From Fig.3, we see that the empirical autocorrelation function fits the first order autocorrelation model very well. Examining the autocorrelation function for $k \geq 0$, as k increases, $R(k)$ decreases exponentially for $a_1 < 1$. Hence, Eq.(17) can be used to described the atmospheric noise temperature measurements. Now, to predict the atmospheric noise temperature l sample ahead, we only need to look at the most recent sample since the process is a first order autoregressive process or a markov process. Let $\hat{y}(t+l)$ be the predicted noise temperature at time $t+l$. we can write

$$\hat{y}(t+l) = c \cdot y(t) \qquad (19)$$

To minimize the prediction mean square error, we have

$$E[(\hat{y}(t+l) - y(t+l))y(t)] = 0$$

Solving for the coefficient c, we have

$$c = \frac{R(l)}{R(0)}.$$

B. *Margin in the adaptive rate transmission scheme*

We first investigate the performance of the adaptive rate transmission scheme when a constant margin is added to the predicted atmospheric noise temperature. The result is presented in Fig.4. The throughput of the adaptive transmission scheme with constant margin is compared with the maximum throughput of the constant rate transmission scheme. The service availability is defined as the fraction of the five minute intervals that the transmissions are successful. Note that to achieve the maximum throughput in the constant rate scheme results in a service availability of 80 percent. In comparison, the ART scheme achieves both a higher throughput and a higher availability than the CRT scheme; even with the constant margin as shown in Fig.4.

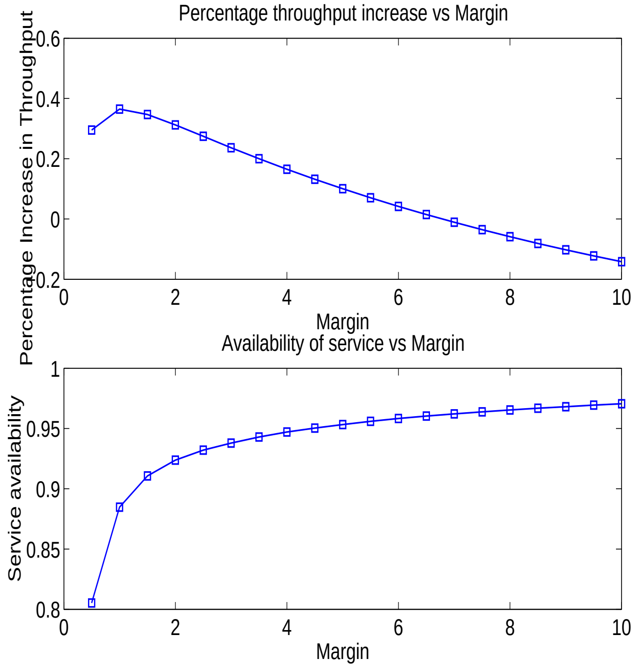

Fig. 4. The percentage throughput increase (as compared to the CRT scheme) and availability in the adaptive rate transmission scheme with a constant margin.

Similarly to the constant rate transmission scheme, we see the tradeoff between the throughput and the service availability. As the margin increases, the throughput decreases and availability increases. Since the sole purpose of adding a margin to the predict atmospheric noise temperature is to mitigate the prediction error, knowing how good the prediction can be very useful in determining the right margin levels. That is, if the prediction is good, it is unnecessary to add a large margin.

Intuitively, if the past atmospheric temperature has little fluctuation, we know the prediction should be good. Also, if the current atmospheric temperature is low (i.e., the weather is good), the predicted temperature in the future is usually more accurate because the atmospheric condition under good weather is less variable compared to poor weather say when a storm system is present. Hence, to estimate the accuracy of the prediction, our adaptive rate transmission scheme will take the following two factors into consideration: the standard deviation of the past atmospheric noise measurement and the current atmospheric noise temperature. To get the standard deviation of the past M measurements, say $\{T(-M+1), T(-M+2), \cdots, T(0)\}$, we use the following,

$$SD(0) = \sqrt{\frac{1}{M}\sum_{i=1}^{M}[T(-M+i) - \bar{T}(0)]^2} \qquad (20)$$

where

$$\bar{T}(0) = \frac{1}{M}\sum_{i=1}^{M} T(-M+i)$$

Fig.5 shows how the prediction error and the standard deviation of past measurements are related for data samples 5000 to 9000. We can see that the prediction error is large

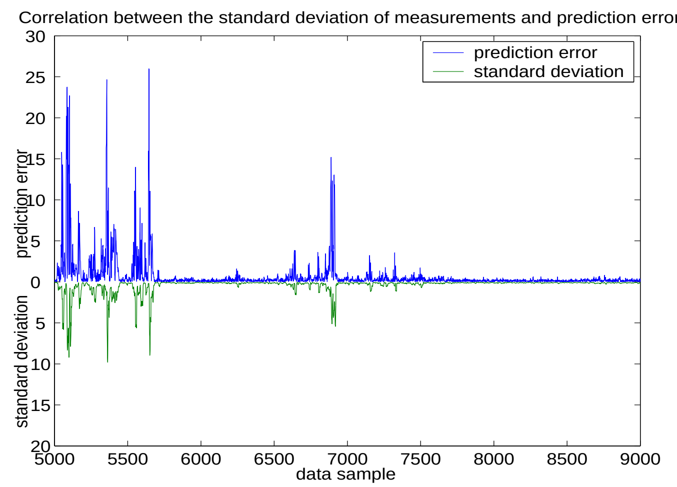

Fig. 5. The correlation between the standard deviation of past measurements and the prediction error.

whenever the standard deviation of the past measurements is large. Fig.6 shows the prediction error and the current atmospheric noise temperature. Low atmospheric noise

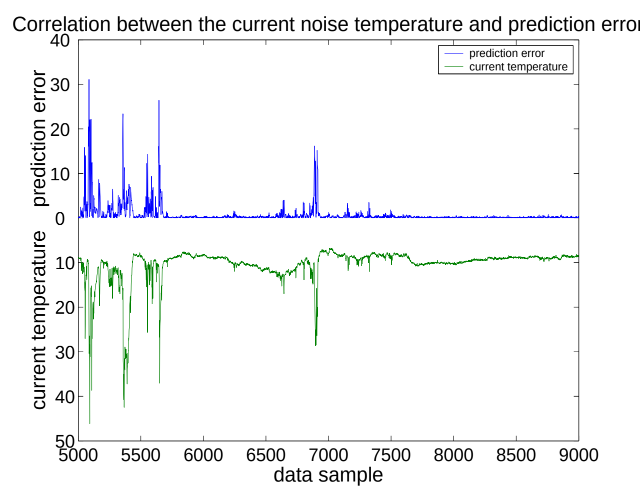

Fig. 6. The correlation between the current measurements and the prediction error.

temperature normally associates with small prediction error.

Based on these two observations, the margin for each five minutes interval is chosen adaptively as follows:

$$\Delta(t) = c_1 \cdot SD(t) + c_2 \cdot T(t), \quad (21)$$

where c_1 and c_2 are constants that can be chosen to achieve a tradeoff between throughput and availability.

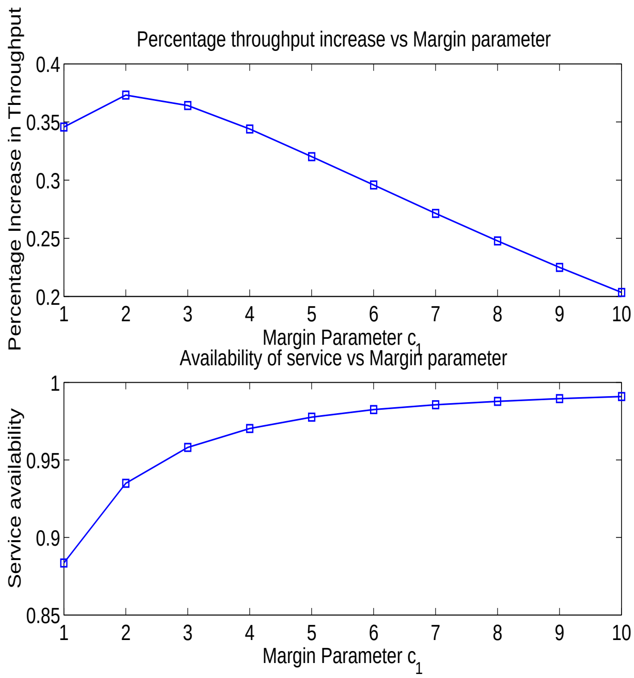

Fig. 7. The percentage throughput increase and availability in the adaptive rate transmission scheme with an adaptive margin.

5. Comparison: Throughput and Service Availability

Fig. 7 shows the performances of the transmission scheme that implements the adaptive margin described in Eq.(21). In this plot, we show how the throughput (compare to that of the constant rate transmission scheme with 80 percent weather availability) and availability changes when c_1 increases. With $c_1 = 2$, the throughput of the adaptive transmission scheme is 37 percent more than the maximum achievable throughput of the constant rate transmission scheme; the service availability is 94 percent, compared to the 80 percent availability of the constant rate transmission scheme. At $c_1 = 10$, the throughput of the adaptive transmission scheme is still 20 percent more than the maximum throughput of the constant rate transmission scheme while the availability increases to 99 percent. Thus, the adaptive rate transmission scheme not only provides significant throughput gain but also greatly increases the data availability.

To make a fair comparison, Fig.1 plots the throughput increase in using the adaptive scheme with respect to the constant rate transmission schemes, for achieving 99, 95, 90, and 80 percent service availability. As we can see from this figure, for the constant rate transmission to achieve 99 service availability, the resulting throughput is only about $\frac{1}{4}$ of that of the adaptive rate transmission scheme.

As mentioned previously, an important advantage of using the adaptive rate transmission scheme is to provide data continuity. Using the constant rate transmission scheme, data will be lost whenever the atmospheric noise temperature is above the threshold temperature, resulting in a complicated retransmission process and mission operational procedure to work around the outage. Fig. 8 presents a histogram of the outage durations using the two different transmission schemes. From the figure, we see that outages occur much more frequently and with longer duration when using the constant rate transmission scheme.

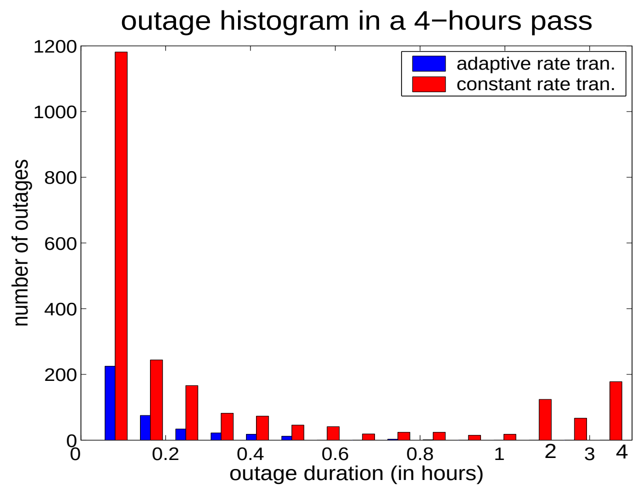

Fig. 8. Histogram of outage duration for both the ART and CRT schemes.

In all the previous throughput results, we assume that the equivalent noise temperature of the ground equipment, T_{eq}, is zero. In Fig.9, we investigate the effect of the throughput performance when the equipment noise is between 0 K and 25 K. For achieving 95 percent weather availability, the throughput increase in the ART scheme with respect to the CRT scheme decreases from 200 percent to 60 percent as the equipment noise increases from 0 K to 25 K.

6. Conclusion

In this paper, we propose a rate adaptive transmission scheme to mitigate the weather effect associated with the Ka-band link while maintaining data continuity and high throughput. During a fixed interval of consideration, the adaptive rate transmission scheme predicts the atmospheric noise temperature one round trip time ahead. The adverse effect of prediction error on the success of the transmission is reduced by dynamically adjusting the link margin.

Our adaptive scheme leads to both a significant throughput increase and a dramatic increase in link availability. For example, when operating at 99 percent availability, our adaptive algorithm achieves a throughput increase of four hundred percent as compared to the constant rate transmission scheme at the same level of link availability.

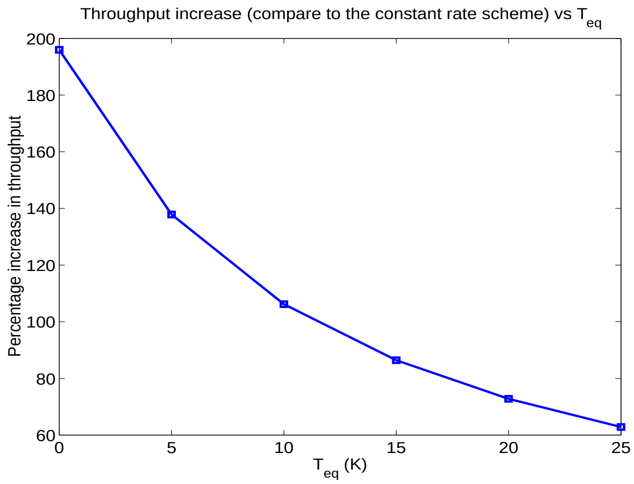

Fig. 9. The effect of equipment noise on the throughput increase.

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