CHALLENGES OF IMPLEMENTING AN INET TRANSCEIVER FOR THE RADIO ACCESS NETWORK STANDARD (RANS)

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ABSTRACT

The Radio Access Network Standard (RANS) is one of the key standards that govern the operation of the iNET Telemetry Network System (TmNS). It defines the network infrastructure over which Test Articles and the Ground Control Stations communicate using the RF network. In the Aeronautical environment, the RAN segment supports the sharing of one RF frequency using a TDMA (Time Division Multiple Access) scheme and provides the mechanisms for antenna handoff and relay capabilities. This paper examines the challenges of implementing the wireless RF transceiver portion of the RANS in support of an upcoming 2012 TmNS demonstration system. Specific topics include the modulation and coding, burst TDMA structure, spectral containment, acquisition of the burst waveform, and efficient data recovery.

KEY WORDS

integrated Network Enhanced Telemetry (iNET), Telemetry Network System (TmNS), Radio Access Network Standard (RANS), Radio Component, C-band, SOQPSK

INTRODUCTION

The iNET project is tasked with upgrading the architecture for flight test telemetry to address the trend in increasing data requirements and decreasing spectrum resources. This represents the first major change to the flight test telemetry architecture in over 50 years. The objectives are to decrease the time and cost associated with test and evaluation, increase system flexibility, make more efficient use of the spectrum, provide two-way connectivity to the test article, and leverage the commercial wireless and networking revolution. The TmNS architecture is the core component of iNET and consists of a Test Article and Ground Station segment which are connected using a bi-directional wireless communication link.

A TmNS demonstration system is being constructed to validate its effectiveness in addressing the list of identified user needs for meeting both current and future flight testing requirements. It is defined by a set of documents outlining the required capabilities, system specification, system design, and test verification. The design identifies a number of system components including the wireless transceiver units for the Test Article and Ground Station. The majority of the TmNS wireless and networking protocol is contained in the Radio Access Network Standard (RANS).

Figure 1 shows a high level documentation summary of the TmNS Demonstration system which includes the top level system documents, a description of the radio related system components and test plans, and the applicable DOD and iNET standards. This paper identifies some of the key challenges in implementing a RANS compliant radio component and provides analysis to ascertain the high risk areas.

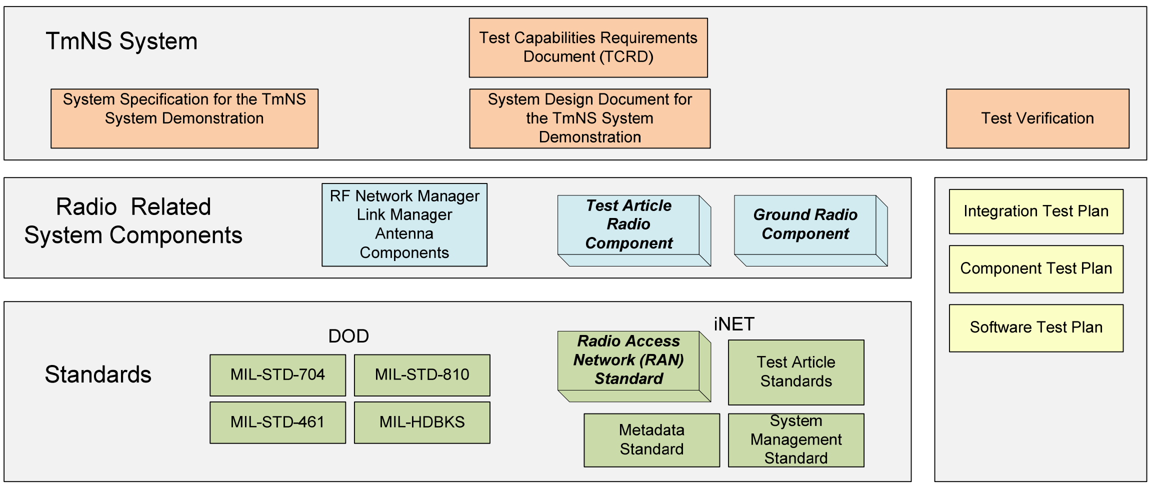

Figure 1. TmNS System Requirements and Standards

RADIO ACCESS NETWORK STANDARD (RANS) DESCRIPTION

The RANS describes the interfaces, protocols, and message definitions for the wireless and network processing in the Test Article and Ground Station Radio Components. A block diagram illustrating a Test Article communicating with a Ground Station is shown in Figure 2. Control and data are exchanged over a single wired Ethernet connection and wireless communications take place over a coaxial RF connection to an antenna. The radios are networked devices and can be individually configured, controlled, and interrogated using the TmNS. Due to differences between the two Radio environments, the TA and GS units each have separate component specifications although a large percentage of the processing is identical.

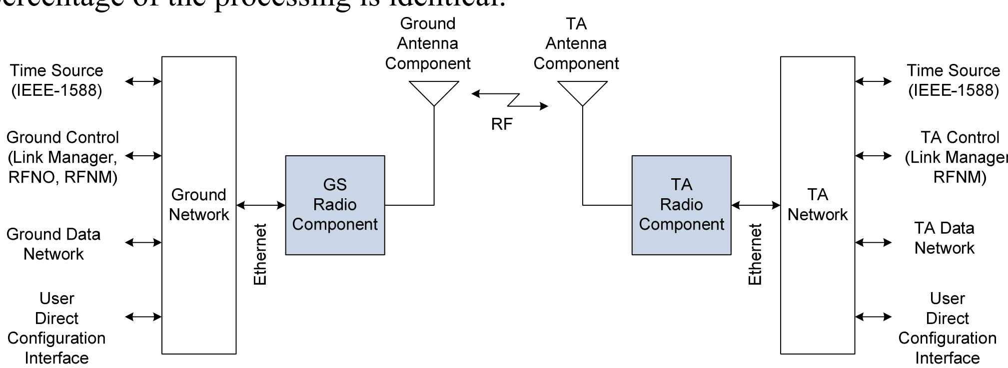

Figure 2. Simplified Block Diagram of RANS Radio Components

Figure 3 shows the layers of messaging described in the RANS. Ethernet frames carry both control and data information. Some of the messages get processed locally, while others get encapsulated into WLAN and HDLC formatted frames, encrypted and presented to the RANS physical layer for wireless transmission via a bi-directional single frequency TDMA RF communication link. The physical layer attaches synchronization segments, performs LDPC forward error correction encoding, and creates a TDMA burst sequence that is transmitted over the air using the spectrally-efficient SOQPSK-TG modulation format. The RANS describes an OFDM modulation mode as well, but for cost and schedule purposes, the demonstration will only include the single carrier mode.

For received bursts, the process is essentially reversed resulting in control and data messages that are either processed locally or passed to either the vehicle network or ground network, depending on whether the unit is on the Test Article or at the Ground Station. Although there are many software challenges in the networking portion of this component, this paper focuses on the performance requirements and risks for implementing the RANS physical layer.

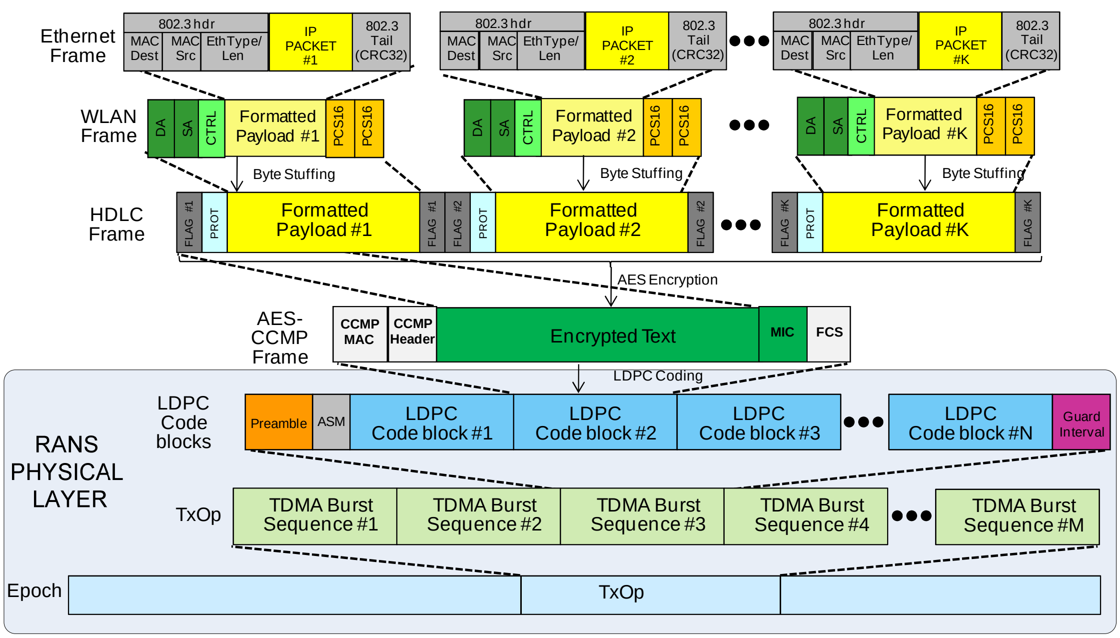

Figure 3. Message processing flow in RANS

RANS PHYSICAL LAYER CHALLENGES

Now that the basic system has been presented, several key challenges for the radio components have been identified and are shown below in Table 1. In addition to the specific items, the table also describes the associated risks. Addressing these potential issues will likely require some specification changes and resolution of certain values that are currently identified but not yet defined. It is envisioned that the standards will continue to be updated through a working group process that is currently ongoing. The following sections examine each of these areas with regard to the specification and whether or not the desired performance is attainable.

Table 1. Key Challenges for the TmNS RANS Radio Component

Challenges	Potential Concerns
RF Band	**Strong desire to move TmNS to C-band to avoid further congestion of L and S bands. The higher propagation loss is approximately compensated for by the larger antenna gain. Potential issues include signal fidelity and burst operation.**
Transmitter Spectral Containment	**Transmitter will not be permitted to operate if spectral emissions are not controlled. Burst TDMA operation and monitoring are new for this community.**
Packet Error Rate	**High PER may cause network data outages and decrease the operating range.**
• **Receiver Acquisition**	**Burst acquisition may limit the ability to recover packets causing data communication outages.**
• **Receiver Sensitivity**	**Receive sensitivity may limit the ability to recover packets causing data communication outages.**
Timing Accuracy	**Precision of TDMA burst timing impacts size of required guard times which affect overhead and efficiency.**
Channel Impairments	**Multipath fading and interference may cause data outages. Antenna pattern variation and tracking error lead to signal variations.**

RF BAND CHALLENGES

Several RF related challenges confront the TmNS Radio component design. In contrast to the traditional serial streaming telemetry, the TmNS Radio must quickly switch between transmit and receive operation on a common frequency and a single antenna port. In addition to designing a high-performance architecture that supports fast R/T turnaround and RF settling, many challenges accompany C-band operation. These include increased attention to EMI/EMC control, minimization of RF trace lengths, budgeting for higher frontend losses, increased roll-off for active components, and design for low phase noise to stay under the IRIG 106 / RANS phase noise mask limits. Fortunately, C-band devices and designs have been shown to provide adequate performance for meeting the RANS performance goals. For example, the sensitivity budget assumes a 5 dB Noise Figure for the Radio component. Current projections and measured data verify that this level of performance is attainable.

TRANSMITTER SPECTRAL CONTAINMENT CHALLENGES

One of the primary issues with a TDMA scheme is controlling the spectral splatter generated when the transmitter ramps up to full power. Design objectives, such as fast channel access to minimize overhead, directly conflict with a controlled slow ramp up period for spectral control. Although the current RANS transmitter ramp-up and ramp-down times are not yet finalized, evidence from actual measurements imply that reasonably short values, in relation to the preamble length, can be used and still meet the IRIG-106 SOQPSK-TG spectral mask for continuous systems. Figure 4 shows how the uncontrolled ramp-up of a periodic burst signal can contaminate the output spectrum, while more controlled transitions can virtually eliminate the unwanted emissions.

Although, using the current IRIG-106 mask is a logical first step, it is recommended that a test method be added to the RANS that is capable of validating the spectral performance of burst signals at rated power output. This would insure that the component performs well dynamically in addition to just statically. Such a test could also assist with system troubleshooting if the TmNS burst equipment causes any unforeseen issues. For demonstration purposes, channel separation can be increased if problems arise.

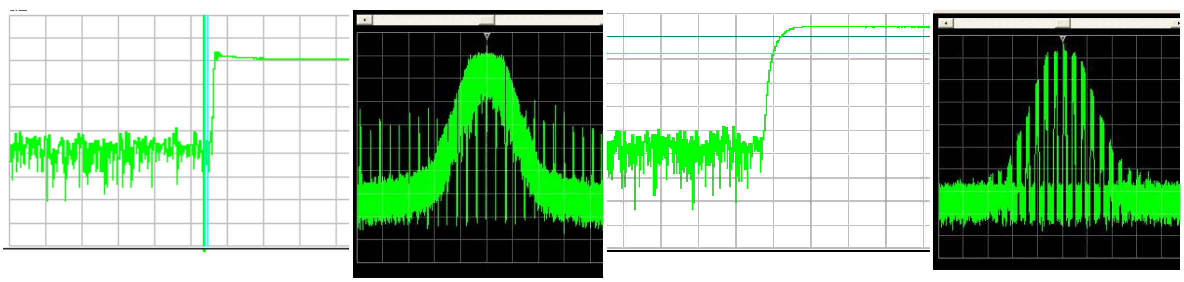

Figure 4. Example of fast rise time with spectral splatter (left) and controlled rise time with no spectral splatter (right).

RECEIVER CHALLENGES

Another key challenge is to recover transmitted messages at less than or equal to the desired Message Error Rate (MER). Failure to do so will result in degraded network performance and loss of operating range. The RANS calls out a receive sensitivity of approximately -92.75 dBm at the input to the Radio component to achieve an effective packet loss of less than or equal to $1x10^{-4}$ for an Ethernet packet size of 1000 bytes which requires a corresponding LDPC codeword error rate (CWER) of less than or equal to $5x10^{-5}$. This assumes a receiver noise figure of 5 dB, implementation losses of 2 dB, and an adjacent interference loss allowance of 1 dB. Assuming that the Noise Figure is within its 5 dB allocation, and that filtering can be added to reduce the effect of the adjacent channel at a cost within the 1 dB loss allocation, that leaves the question of whether or not the core modem sensitivity can achieve the desired MER at a Channel bit to Noise ratio (Ec/No) of 2.5 dB.

The basic transmission format consists of an alternating phase portion (Preamble) for burst synchronization, an Asymmetric Sync Marker (ASM) for codeword framing, and from one to eight LDPC Codeblocks as shown in Figure 5. In an attempt to gain insight into the specification, it is instructive to model the modem in several pieces including an Acquisition, Detector, Demodulator, and LDPC Decoder function as shown in Figure 6. Again, the intention of the specification is to achieve a MER of less than or equal to $1x10^{-4}$ with an Ec/No of less than or equal to 2.5 dB.

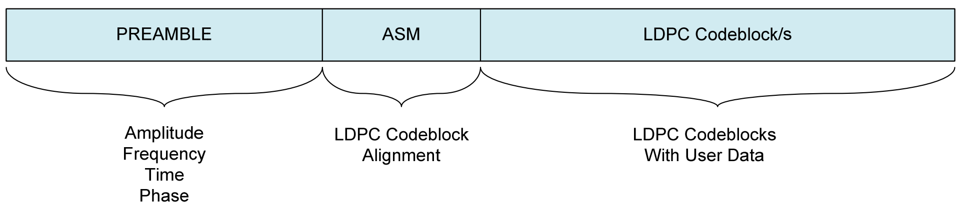

Figure 5. Burst Transmission Structure from RANS

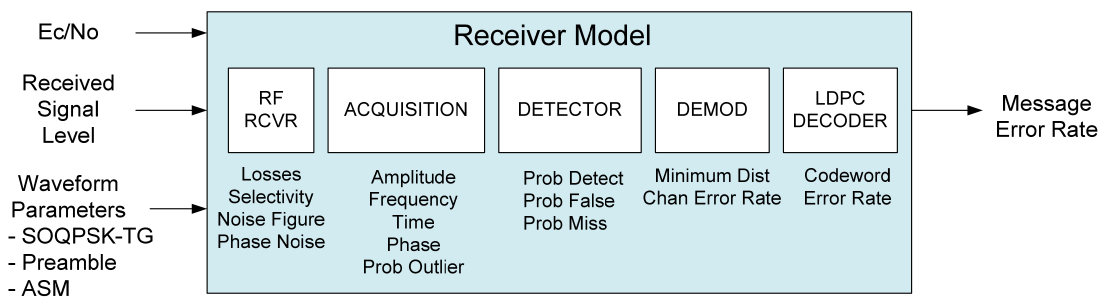

Figure 6. Receiver Model for analyzing RANS Performance Specifications

Fundamentally, the receiver must synchronize, detect, demodulate and decode the transmitted burst with sufficient reliability to meet the desired MER. A mathematical model was constructed to characterize the behavior of each function for purposes of gauging whether or not the specification is acceptable in its current form or needs modification. Based on the synchronization error probability distributions at a particular Ec/No, the distribution for loss in performance due to timing and phase offset can be calculated and used to compute the probability that the channel error probability (Pc) is less than the maximum allowable Pc_{max} that yields the desired $1x10^{-4}$ MER. This calculation provides insight into how much margin is needed to account for synchronization.

The calculation process is shown in Figure 6 and uses the Cramer' Rao bound to calculate the statistical performance of the ability of the acquisition function to estimate frequency, timing, and carrier phase as a function of Ec/No and preamble structure assuming Maximum Likelihood parameter estimation.

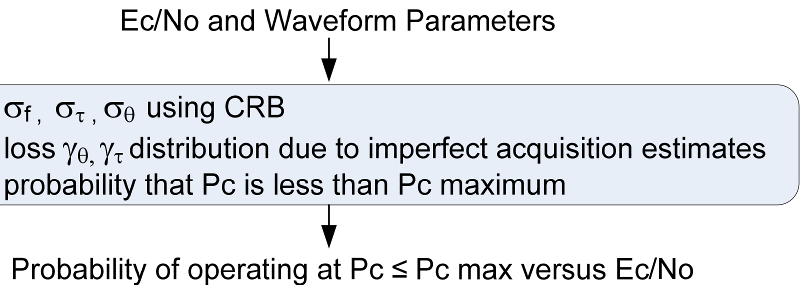

Figure 6. Calculation procedure for determining the performance margin versus SNR

In addition to achieving the MER based solely on this type of transfer function approach, other issues must be considered including the probability of an outlier frequency estimate, missed detection, or a false alarm as any of these will likely result in a message failure. The likelihood of these events has to be much smaller than the desired MER to not degrade system performance. Table 2 shows the calculation details and rationale.

Table 2. Details of Receiver Model Calculations

Calculation	Method	Comments
Cramer Rao Bound gives the minimum variance of frequency, phase, and time estimates given Ec/No and the specified observation interval	$\sigma_f \geq \sqrt{\frac{12}{(2\pi)^2}\frac{1}{T_{obs}^2}\frac{N_0}{2L_sE_s}}$ Hz $\sigma_\theta \geq \sqrt{\frac{4N_0}{2L_sE_s}}$ Rad $\frac{\sigma_\tau}{T_s} \geq \sqrt{\frac{N_0}{2\pi^2 L_sE_s}}$	L_s = symbols in observation E_s = Energy per symbol T_s = symbol time T_{obs} = observation length N_o = Noise spectral density τ/T_s= Normalized timing error
Probability of Outlier	$P_{Outlier} = \frac{1}{L_s}\sum_{m=2}^{L_s}\frac{L_s!(-1)^m}{(L_s-m)!\,m!}\exp\left(-L_s\frac{E_s}{N_0}\frac{m-1}{m}\right)$	Probability that Acquisition estimate will be an outlier due to nonlinear threshold effect.
Loss due to static phase and timing offsets	$\gamma_\theta = \cos(\theta)$ $\gamma_\tau \approx \sin(\pi\,\tau/T_s)/(\pi\,\tau/T_s)$ $Loss\ in\ dB\ due\ to\ sync = 20log10(\gamma_\theta\gamma_\tau)$	Loss due to phase offset. Approximate loss due to small normalized timing offset. Loss due to imperfect synchronization.
Resulting Channel Error Probability	$P_c \leq \frac{1}{2}Q\left(\sqrt{1.6\gamma_\theta^2\gamma_\tau^2\frac{E_c}{N_0}}\right)+\frac{1}{2}Q\left(\sqrt{2.59\gamma_\theta^2\gamma_\tau^2\frac{E_c}{N_0}}\right)$	Approximation for resulting channel error probability with synchronization loss and no differential encoding. Modification to RANS D.1.4.1.
Probability of Detection, Miss, and False Alarm	$P_d = \sum_{k=n1}^{n}\binom{n}{k}(1-P_c)^k\,P_c^{n-k}$ $P_{fa} = \sum_{k=n1}^{n}\binom{n}{k}(1/2)^n$	P_d, P_m = 1-P_d based on assuming a correlator architecture with threshold n_1 out of n channel bits with n_1 selected based on n and Pc_{max} for a Pd ≥ 0.99999. False alarm based on threshold with no signal present.
LDPC Codeblock Error Probability	Achieving desired $5x10^{-5}$ CBER requires input channel error rate to be less than or equal to Pc < 0.067 (≜ Pc_{max}).	From RANS reference curves (Figure 12-63) and Table 12-12 stating that ideal demodulator needs 2.25 Eb/No to achieve desired $1x10^{-4}$ MER.
Message Error Probability from Codeblock Probability	Standard assumes 5e-5 CBER is required to achieve desired 1e-4 MER based on $CBER = 1 - \sqrt{1-PLR}$	From RANS 5.1.1.1

Figure 7 illustrates the relationship between the channel error and decoder codeblock error probability and shows an example of loss versus synchronization error. The red vertical line identifies the Pc_{max} that corresponds to the maximum allowable channel error rate that can still meet the specified $5x10^{-5}$ CBER and corresponding $1x10^{-4}$ MER. Figure 8 shows the probability of Pc exceeding Pc_{max} versus Ec/No for the currently specified preamble length (64 symbols) as well as the results for 32 and 96 to get an idea of how the required Ec/No margin changes as a function of preamble length. The curves show that it requires an additional 0.54, 0.8, and 1.43 dB from the reference curve for a respective 96, 64, and 32 symbol length preamble. With a channel error rate of Pc_{max}, an acceptable probability of detection, miss, and false alarm are possible at 64 symbols as well as a very small outlier probability that are low enough not to adversely impact the desired MER.

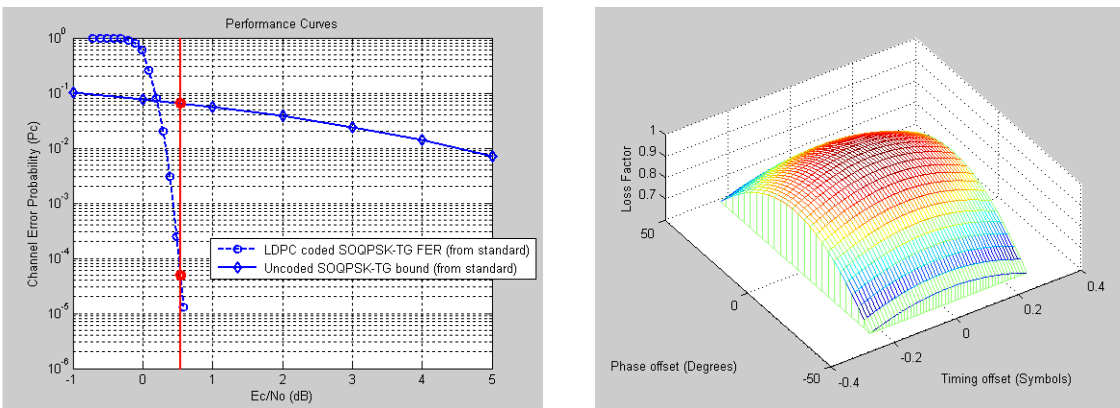

Figure 7. Uncoded Pc and Coded CBER (left), Sync error surface (right)

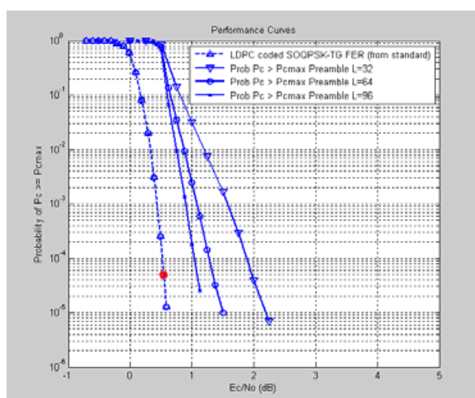

Figure 8. Probability that Pc > Pc_{max} versus Ec/No for various preamble lengths

With a total implementation loss allowance of 2 dB in the current specification, and at least 0.8 dB of loss due to synchronization, there is only 1.2 dB of margin to account for the non-ideal transmitter, RF front end imperfections, loss of usable preamble due to ramp-up, and deviations from the receiver maximum likelihood processing assumptions due to size, weight, and power trade-offs. The consequence of not meeting the sensitivity specification is a reduction in range. This analysis is primarily intended to assist in the effort to finalize the RANS and help provide insight into some of the performance versus size, weight, and power trade-offs.

TIMING ACCURACY CHALLENGES

The RANS specifies a timing accuracy of +/- 1 us for generation of the TDMA burst at its designated time. This requirement demands better than 1 part per million (PPM) timing accuracy which is provided by an external IEEE-1588 timing source. Although this is a mature standard with available off-the-shelf implementations, it is a challenge to maintain this level of timing accuracy throughout the various digital and analog processing components. In addition to achieving the required burst and epoch timing, other system level architectural challenges include pushing timing between red/black boundaries and maintaining alignment of multiple IEEE-1588 sources. The consequence of having to increase the allowable timing error would be larger guard times resulting in a small reduction in network efficiency. It is suggested that the RANS be updated to include the desired behavior if it is determined that the timing accuracy is degraded beyond the current requirement if outages or flywheeling degrade performance. It should also specify the maximum error such that a Radio will not be permitted to transmit in the TDMA network. Since the radio is a networked device, it can report error conditions to the Network manager as soon as a problem is detected.

CHANNEL IMPAIRMENT CHALLENGES

Channel impairments due to multipath, blockages, or pointing loss were not included in the previous analysis, but are treated as a loss allocation in the link budgets presented in the RANS. Currently, 3 dB is allocated for antenna gain variation/multipath and 1 dB for ground station antenna pointing loss. Antenna pattern variations can be relatively large on the Test Article due to the pattern itself, blockage due to the airframe, orientation between transmit and receive antennas, and potential interaction between top and bottom antennas if applicable. With relatively low link margins, compared to a standard serial streaming telemetry link budget, this could be an area of concern. Testing will be conducted in the lab using the multipath parameters specified in the RANS. This level of testing will help uncover any algorithmic or RF related vulnerabilities early on and increase the confidence of successful flight testing.

A recent addition to the RANS is the ability to perform ARQ (Automatic ReQuest repeat) of failed packets at the MAC layer. This feature may help alleviate the impacts of intermittent communication outages. Lab and flight testing in 2012 will be conducted to assess the overall effectiveness of this capability and determine if any radio or system level issues arise due to channel related impairments.

CONCLUSIONS

This paper examined the challenges in realizing and specifying iNET transceivers for the upcoming TmNS system. It identified key risk areas and investigated whether or not the desired performance levels were attainable along with the potential system consequences. Items presented included the top-level system and component documents, a description of the Radio components, and analysis and recommendations regarding the RANS document. In general, the Radio component should be able to meet or exceed its key performance objectives. With the exception of an antenna tracking failure or the presence of severe multipath fading, the TmNS radio component should perform well. Areas that still need to verified experimentally at the PHY level include system operation at C-band, spectral emissions and timing of the burst signal generation, received message reliability with and without ARQ, and sensitivity to channel impairments. Suggested modifications to the existing RANS include:

RANS Item	Section	Comments
Spectral Containment	5.1.2.1	Add method for spectral validation of burst TDMA signals.
Sensitivity	5.1.3.1.1.3 5.1.3.1.2.3	Possibly increase implementation margin due to SWAP trades. Specify a confidence level for packet loss rate (PLR) for test purposes.
Preamble	5.1.6.1.1.2	Possibly increase preamble/ASM lengths due to RF settling time or SWAP trades.
ARQ	New	Details of an ARQ approach are current being addressed through the RANS working group.
Link Budget	B.1.6.3	Review of the margins allocated for antenna gain variation/multipath and pointing loss.
Timing Accuracy	5.1.3.1.1.6	Add description of desired behavior when timing accuracy exceeds allowance.

ACKNOWLEDGEMENTS

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