DELAY SPREAD CHARACTERIZATION OF THE AERONAUTICAL CHANNEL.

Authors: Ibrahim Fofanah, Wannaw Assegu
Advisors: Dr. Arlene Cole-Rhodes, Dr. Richard Dean, Dr. Farzad Moazzami
Department of Electrical and Computer Engineering
Morgan State University
ibfof1@morgan.edu, waass1@ morgan.edu

ABSTRACT

Radio transmission channel influences greatly the quality of transmitted voice and data signal in terms of data rate and robustness. This degradation is as a result of many factors, notable amongst them are having multiple replica of the transmitted signal at the receiver (multipath), changes of frequency as a result of the movement of the aircraft (Doppler shift) and noise.
This paper characterizes the scattered components of the aeronautical channel in terms of delay spread. Geometric representation is used to derive expressions for the maximum delay spread using the 2-ray model and the three dimensional model of the scattered path. Furthermore, the delay and Doppler frequencies are described as a function of the horizontal distance to the specular reflection point between a ground station and a test article. The simulated results are compared to measured data of related articles and the value of the maximum delay spread is compared with the proposed intersymbol guard band for Orthogonal Frequency Division Multiplexing (OFDM) in the Integrated Network Enhanced Telemetry (iNET) program to see if this proposition can be adapted to the aeronautical channel.

KEY WORDS

OFDM, TDMA, Delay Spread, Multipath, Doppler shift

1. INTRODUCTION

The communication channel is the physical medium between the transmitter and the receiver [1]. The free-space channel model that treats the region between the transmit and receive antennas as being free from all objects that might absorb or reflect radio frequency energy is not adequate to describe a realistic aeronautical channel. A realistic aeronautical channel must be utilized for communication between an aircraft and a base station (air - to- ground communication or ground- to- air communication) and between aircrafts (air-to-air) communication. This medium influences greatly the performance of signals in terms of data rate and robustness. Thus a thorough knowledge of how this medium operates will help greatly in system design and evaluation.

Many factors influence greatly the performance of the aeronautical channel including multipath propagation, Doppler effect, additive noise and delay spread. The integrated Network Enhanced Telemetry (iNET) [2] has proposed Time Division Multiple Access (TDMA) structure with a maximum channel delay spread of 0.40μs for the 100 nm range and Orthogonal Frequency Division Multiplexing (OFDM) multicarrier modulation scheme supporting radio air user data.

In this work, we use the two and three –ray models to simulate the maximum delay spread of the aeronautical channel and then show how this value compares to the Orthogonality of OFDM symbols.

The rest of the paper is structured as follows. Section 2, provides a detailed discussion of the parameters that affect radio propagation with special emphasizes on delay spread of the aeronautical channel. In section 3, we discussed briefly the 16-QAM Convolutional coded OFDM structure. Section 4 provides computed results for iNET TDMA structure. Simulation results for the delay spread and 16-QAM multicarrier system are provided in 5. Finally, conclusions are provided in section 6.

2. AERONAUTICAL CHANNEL PARAMETERS

Varying channel conditions are associated with different stages of the flight of an aircraft. Notable amongst these are Doppler, delay spread and fading. The Doppler and delay spread are used to characterize the direct wave and the scattered components of the channel. Rician K factor, defined as the ratio of signal power in dominant component over the scattered/diffused power, is very important in understanding the behavior of a wireless channel. It determines the distribution of the received signal amplitude. Knowledge of the Rician *K* factor can be useful in determining the bit error rate of a channel among other useful metrics [3].

The *K*-factor can be estimated from a set of different samples of the channels, for instance at different frequencies. Equation (1) relates LOS and the diffused component of the multipath called the Racian factor,

$$K_{Rice} = \frac{a^2}{c^2}$$

and in decibels

$$K_{Rice} = 10log_{10}(a^2/c^2) \tag{1}$$

a is the amplitude of the LOS component and c^2 is the variance of the scattered component.

As shown in [3], if we assume a constant multipath faded envelope ie $\sqrt{a^2 + c^2} = 1$, then the amplitude of the LOS and diffused components are obtained from equation 1 as follows:

$$a = \sqrt{\frac{K_{Rice}}{K_{Rice}+1}} \tag{2}$$

$$c = \sqrt{\frac{1}{K_{Rice}+1}} \tag{3}$$

As $\mathrm{K_{Rice}} \to 0$ we get Racian fading ie strong LOS path component and $\mathrm{a} = 0$and $\mathrm{c} = 1$. Similarly, as $\mathrm{K_{Rice}} \to \infty,$ we obtained $\mathrm{a} = 1$ and $\mathrm{c} = 0$ this is a Gaussian distribution.

2.1 Doppler Frequency

Most of the stages associated with the test article movements are characterized by fast fading [3]. Doppler has a major impact on OFDM bases systems. OFDM sensitivity to frequency shifts results in intercarrier interference (ICI) and degrades spectral efficiency. High mobility platform associated with aircrafts, offer a challenging environment for OFDM.

The maximum and minimum Doppler frequency associated with air– to -air communication is the sum of the velocities of the test two articles.

$$f_{d,max} = \pm \frac{(V_R + V_T)}{c} f_c \tag{4}$$

Also the maximum and minimum Doppler for ground-to-air communication is

$$f_{d,max} = \pm \frac{V_T}{c} f_c \tag{5}$$

Where:

V_T and V_R are the velocities of the transmitter and receiver respectively.

f_c is the carrier frequency

c is the speed of light

The Doppler spectrum scattered components are normally non-isotropic and the Doppler probability density function is the classical 2-D isotropic Doppler density function derived in [4].

$$p(f_d) = \begin{cases} \dfrac{1}{\pi f_{d,max}\sqrt{1-\left(\frac{f_d}{f_{d,max}}\right)^2}}, & |f_d| < f_{d,max} < 0 \\ 0, & \text{else} \end{cases} \tag{6}$$

In table 1, we computed the maximum Doppler associated with a test article flying with a speed of Mach 2 for air-to-air communication and ground-to-air communication.

Carrier Frequency	5GHz
Speed	Mach 2
Max. Doppler Frequency (air-to-air communication)	$\pm$22KHz
Max. Doppler Frequency (ground-to-air communication)	$\pm$11KHz
Channel Stationarity	0.1ms

Table1: Computation Parameters

2.2. Channel Fading

Communication between two aircrafts and/or a basestation and an aircraft is normally characterized by multipath components, which is a combination of direct line of sight component (LOS) and reflected path components. Two types of fading are prominent on the channel between test articles and test article and basestation. Fast fading also called multi-path fading, is a result of multi-path propagation and occurs when multi-path signals arriving at the receiver, the constructive and destructive phases create a variation in signal strength. Similarly, slow fading also called shadowing results when the test article moves away from a basestation the signal strength drops down slowly.

In this model, the direct path is modeled as a constant envelope and the diffused component as a Rayleigh process [3]. Also, the delays and attenuations of the N multipath are varying in time, due to the high mobility of the test article. The corresponding model for the channel impulse response in time is presented in equations (7)

$$h(\tau, t) = \sum_{i=0}^{N-1} a_i\,(t,\tau)\exp\{(j2\pi f_d \tau_i(t)) + \varphi_i(t,\tau)\}\delta(\tau - \tau_i(t)) \tag{7}$$

where:

$a_i(t,\tau)$: is the path gain

$\tau_i(t)$: represents the time delay of the i^{th}multipath component

$\delta(\tau - \tau_i(t))$: is the impulse transmitted into the system at time t.

$\exp\{(j2\pi f_d \tau_i(t)) + \varphi_i(t,\tau)\}$ this term quantifies the phase shifts of the various multipath components.

2.3. Delay Spread

The two-ray model shown in figure (2) is normally reasonably accurate for predicting signal strength over very large distances [5].

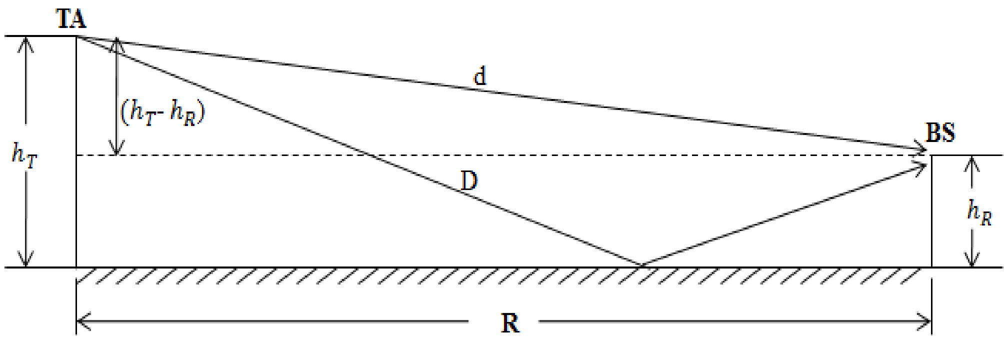

Figure 2: Test Article position from the basestation

2.3.1. Geometry of the Scatterer for 2-Ray Model

The path difference $d\Delta$, between the line-of-sight and the ground reflected path is calculated using the method of image reflection.

Let the height of the base station and the altitude of the aircraft be h_r and h_t respectively. Furthermore, the distance between the basestation and the test article be represented as R. Δd is the differential distance, that is the path difference between the reflected path length D and the direct path length d. The direct path and the reflected path lengths d and D in terms of base station antenna height, aircraft altitude and separation distance R are respectively shown in equations (9) and (10).

$$d = \sqrt{R^2 + (h_t - h_r)^2} \tag{8}$$

$$D = \sqrt{R^2 + (h_t + h_r)^2} \tag{9}$$

The differential distance is as expressed below:

$$\Delta d = D - d = \sqrt{R^2 + (h_t + h_r)^2} - \sqrt{R^2 + (h_t - h_r)^2} \tag{10}$$

Thus the delay spread between the reflected ray path and the direct path over a plane earth in terms of the velocity of light c is

$$\Delta t = \frac{D-d}{c} \tag{11}$$

2.3.2. Geometry of the Scatterer 3-Ray Model

Here, the transmitted signal of an aircraft flying at a known distance from the base station hits a mountainous surface and reflected at the same angle to the base station.

Let γ, represents the bore sight angle, which is the angle the test article makes with the reflecting surface and *i*, the reflected ray angle to the base station. The reflection point always constitutes of two congruent angles because the signal always travels towards the receiver in the same angle that it was reflected as shown in figure 3 below.

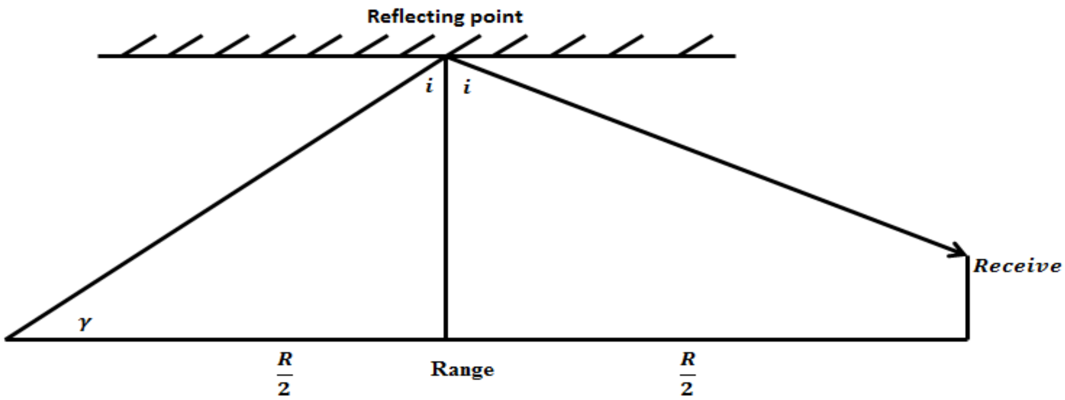

Figure 3: Geometry for 3-path propagation

From geometry, we derived expressions for the boresight angle, differential distance and the direct path length (*R*).

The bore sight angle, $$\gamma \cos(\gamma) = \frac{R}{2D} \quad (12)$$

The total reflected path, $$2D = \frac{R}{\cos(\gamma)} \quad (13)$$

The differential distance, $$\Delta d = \frac{R}{\cos(\gamma)} - R \quad (14)$$

The delay spread in seconds, $$\tau = \frac{\Delta d}{c} \quad (15)$$

Then Path gain $H = \beta\big(cos(\gamma)\big)^2, \beta\ is\ the\ reflection\ coefficient$

3. ORTHOGONAL FREQUENCY MODULATION MULTIPLEXING (OFDM) SYSTEM DESIGN

The OFDM system transmission scheme is shown in figure (4), here the input binary data stream is encoded for error correction, before the encoded data is 16-QAM modulated and then OFDM modulation is done using IFFT algorithm and pilots are inserted. Before getting to the channel, guard interval is added to mitigate inter carrier interference (ICI).The OFDM modulated signal is convolved with the channel and AWGN is added after that the guard interval is removed and FFT is done. Channel estimation is done followed by demodulation, and then Viterbi decoding.

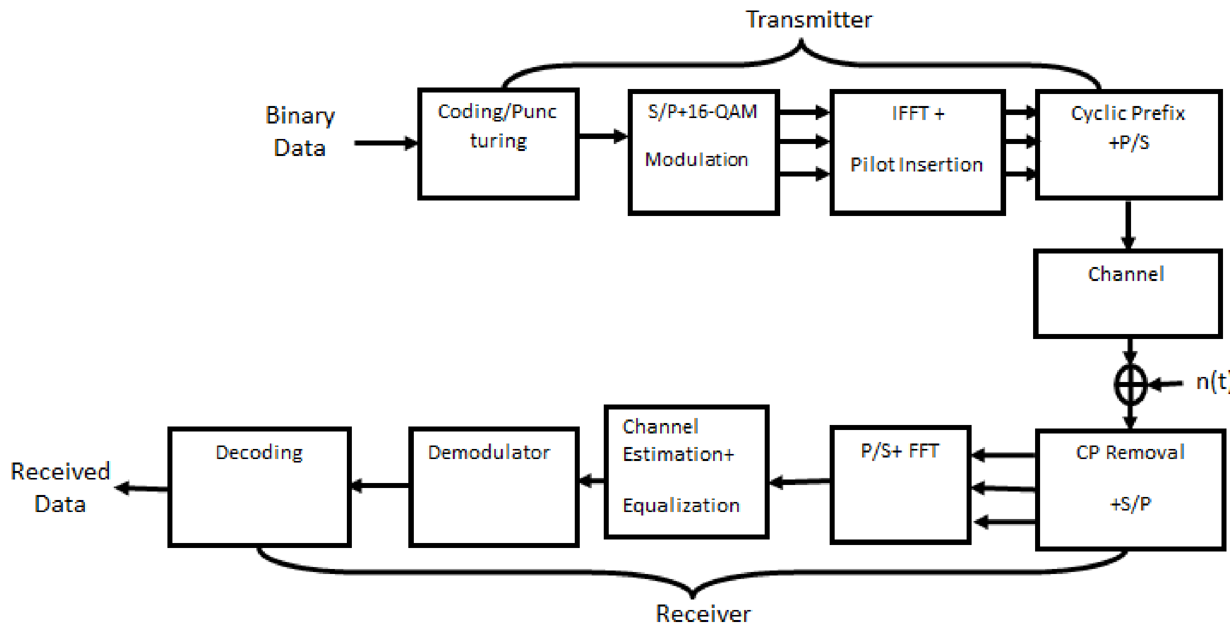

Figure 4: Coded 16-QAM OFDM system with pilot assisted channel estimation

4. INET TDMA/OFDM STRUCTURE

The base reference to this project was presented in [5] which is adapting TDMA/OFDM for data/voice transmission between test articles or test articles and base stations. In our analysis, the digitally generated signals are divided in time and are easily reconfigured for changing traffic demands. These signals are resistant to noise and interference and can readily handle mixed voice, video, and data traffic. One major advantage of TDMA when using the entire bandwidth of iNET is only one signal is present in the iNET transmission band at a given time. Nonlinearity in the band can cause an increase in inter symbol interference with digital carriers. The two criteria considered to adapt OFDM to iNET TDMA structure are the rfNET aeronautical specification and the IEEE802.11a standard.

The design Parameters are calculated based on the rfNET Aeronautical requirement and bandwidth and network capacity (threshold) tables provided in [5] and Nyquist bandwidth $0.5\mu s$ (Fs) criterion, These are shown below.

Nyquist bandwidth	20 MHz
sampling rate (T_s)	0.05 µS
Symbol period ($N\ T_s$)	3.2µS
Net Transmission (Tx) time	3404 µS
Number of Frames	14
Frame period	242.123 µS
Number of OFDM symbols	61

Table 2: Calculated Designed rfNET Parameters

5. SIMULATED RESULTS

5.1. Delay Spread for 2-Ray Model

In figure 4, based on equation (11), we show the delay spread for air-air- links with maximum distance being 1 – 37km from the basestation with transmit and receive heights set at 10000 and 1000 meters respectively. For the two ray model, we obtained delay spread value of approximately 6.7µS and this value is far greater than 0.8 µS which is the guard band for 802.11a standard.

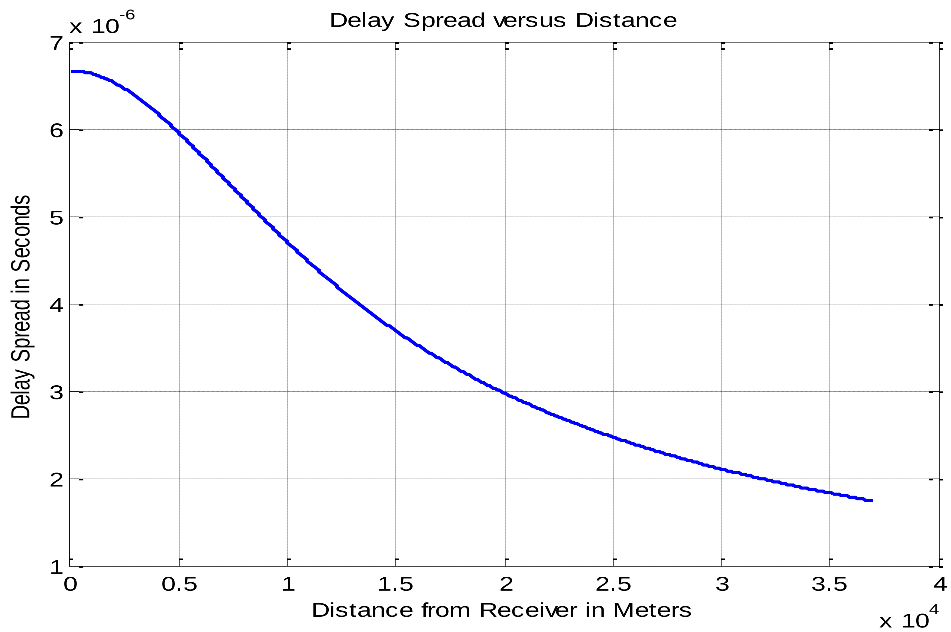

Figure 5: Delay Spread Versus Range

5.2. Effect of Delay Spread on OFDM Symbols Orthogonality

In the results that follow, we show the effect of delay spread on OFDM symbols orthogonality considering the following cases:

- Delay spread larger than the cyclic prefix length
- Delay spread smaller than the cyclic prefix length

The final results show that the possible solution of improving channel performance could be using higher order FFT size.

5.2.1. Delay Spread Longer Than the Cyclic Prefix Length

In this case the guard interval is not long enough to combat channel frequency selectivity and the orthogonality condition among tones does not hold anymore. Figure (6) demonstrates this by using FFT 64 –point CP=8 and 32 tap channel where the CP is not long enough to account for the delay spread the performance of the Coded, and Coded with equalization are lower. As we can see the equalizer has gotten an irreducible error rate after symbol error rate of 10^{-2} and the coding with equalization about 10^{-3}which is the maximum achievable error rate.

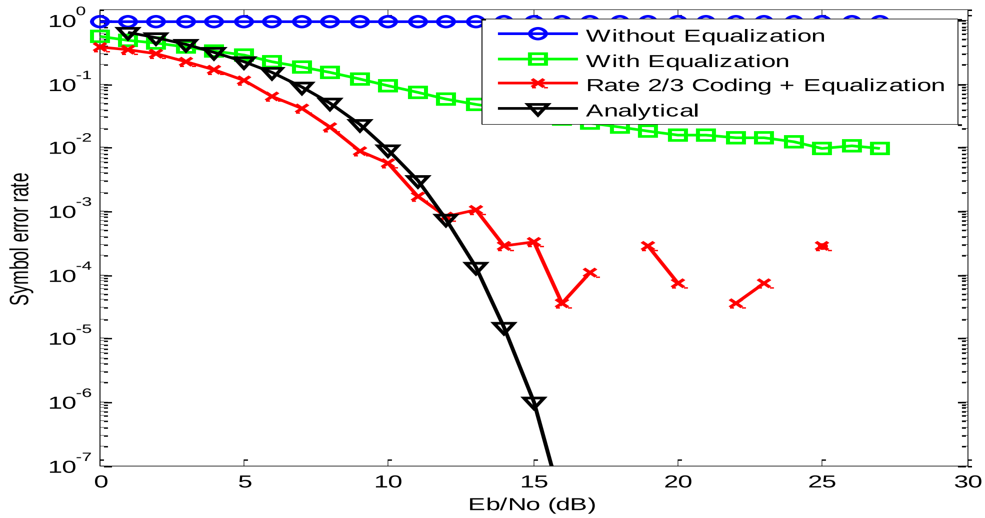

Figure 6: Performance of OFDM system with delay spread longer than CP

5.2.2. Delay Spread Shorter Than the Cyclic Prefix Length

In this case, the transmitted information can be completely recovered by multiplying the received symbols by the inverse of the channel, if the channel is perfectly known. Figure (7) demonstrates when the delay spread is less than the CP length the equalizer, and coding with equalization performs to the desired error performance rate.

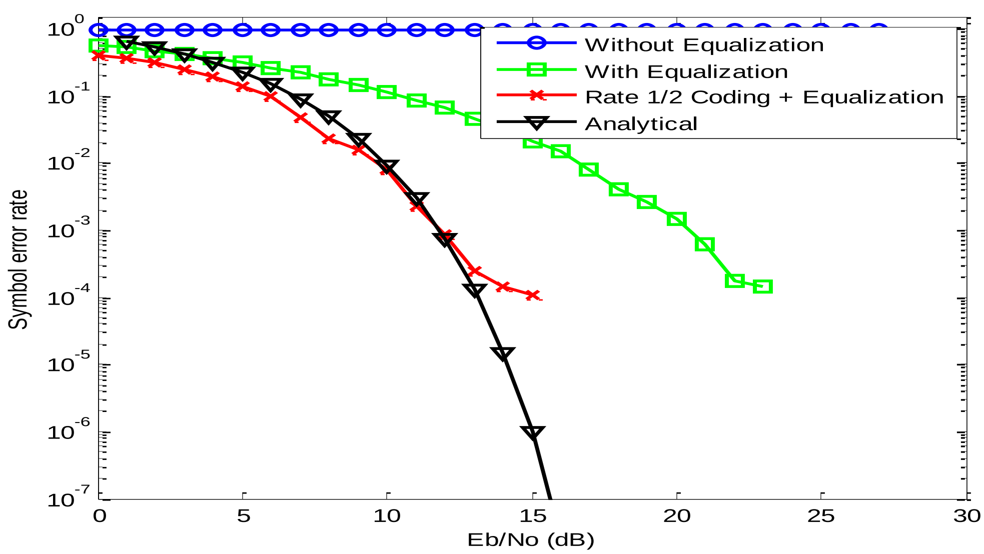

Figure 7: Performance of OFDM system with delay spread lshorter than CP

5.2.3. Performance Of 64-Point versus 128-Point FFT

Figure (8) shows that the performance of 16-QAM convolutional coded OFDM can be improved by increasing the FFT size. In figure (8b), we see that the 128-point FFT performs well for the coded, and the coded and equalized even though the delay spread is longer than the $0.8\mu s$

intersymbol guard band. In figure (8a), we see that with 64-point FFT we have irreducible error for coding, and equalization and coding. With a delay spread of 0.8μs, the 128 point FFT size out performs the 64 point FFT size because the guard interval have been doubled.

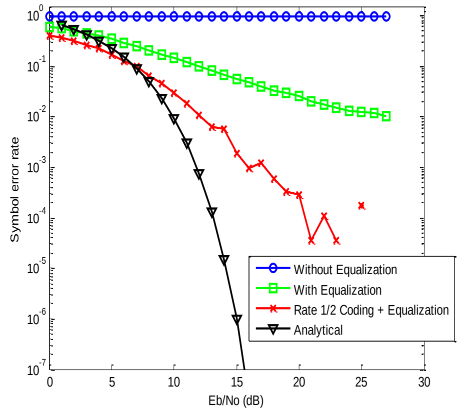

Figure 8a: 64-FFT CP<delay spread

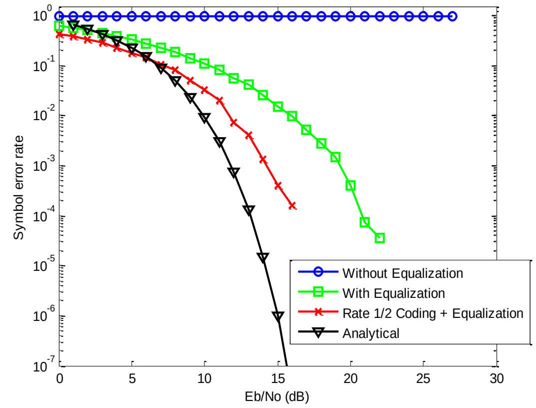

Figure8b: 128-FFT CP<delay spread

Figure 13: Comparison of performance of 64 and 128-point FFTs with the same delay spread

6. CONCLUSION

In this paper, the maximum delay for en-route air-air communication was computed and the value followed closely with empirical data presented in [3]. Furthermore, we demonstrated that 0.8 µsec CP guard band for wireless LAN might not be applicable for iNET air-craft to ground communication. Finally we show that by increasing the FFT length we are able to compensate for the performance of coded, coded and equalized 16-QAM OFDM at values of delay spread greater than the cyclic prefix length.

7. ACKNOWLEDGMENT

The authors would like to thank TRMC, SRC and CSC for their support. We would also like to express our sincere appreciation to our supervisors Dr. Richard Dean, Dr. Arlene Cole-Rhodes and Dr. Farzad Moazzami for their unweaving supports.

Bibliography

[1] John G Proakis, *Digital communications*, 4th ed. New York: McGraw Hill, 2001.

[2] iNET. (2010, February) Communication Link Standard. [Online]. https://www.inetprogram.org

[3] Erik Haas, "Aeronautical Channel Modeling," in *IEEE* Transaction *on Vehicular Technology*, 2002, p. 254.

[4] R.H. Clarke, "Statistical theory of mobile-radio reception," in *Bell Syst. Tech J.*, 1968, pp. 957-1000.

[5] Boeing /lattice communication Paul Norris, "Radio Frequency Technologies to Support iNET," in *ITC*, 2010.