# Submission to
# IEEE P802.11
# Wireless LANs

Title: **Sliding DFE and MLSE/DFE Packet Error Rate Performance for QMBOK AND MBOK**

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**Abstract**

This submission presents a full suite of packet-error-rate performance curves for the thermal-only, multipath-only and combined thermal-multipath test cases. This data supports the packet-error-rate numbers described in the HARRIS 2.4 GHz proposal [1].

# 1. Introduction

This submission presents a full suite of packet-error-rate performance curves for the thermal-only, multipath-only and combined thermal-multipath test cases. This data supports the packet-error-rate numbers described in the HARRIS 2.4 GHz proposal [1]. Section 2 presents sliding DFE data. Section 3 presents sliding MLSE/DFE data.

# 2. Sliding Decision Feedback Equalizer (DFE) Performance

## 2.1 Description of Simulation

The graphs that follow contain simulation data only. The specifics about the waveform used for transmission is described in the HARRIS proposal ("Multipath Issues and Architectures", doc:IEEE P802.11-98/37, January 1998). No frequency offset or phase jitter was introduced. Transmit filters consist of a NRZ pulse shape filter, 7.7MHz, $5^{th}$ order Butterworth and SAW combination. The receive filters consist of the same 7.7MHz, $5^{th}$ order Butterworth and SAW combination. The transmit/receive filter chain is shown in Figure 2.1.

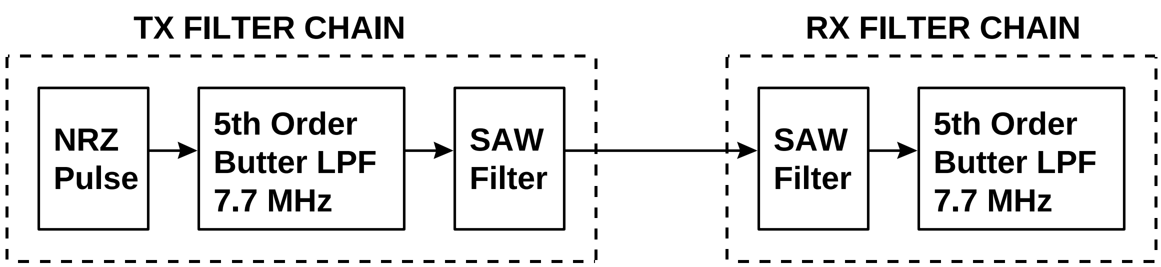


**Figure 2.1 - Simulated transmit/receive filter chain**

The channel may consist of any combination of thermal noise and/or the baseline exponentially decaying Rayleigh fading channel model with various rms delay spreads. The Butterworth and SAW combination was used to limit the noise and effects of adjacent channels. Unequalized performance is compared against "ideal" transmit and receive matched filters, specifically 50% root raised cosine. The sample data, one complex sample per chip, is sent through the sliding decision feedback equalizer. The channel impulse response estimation is fed through a zero forcing algorithm to produce the DFE filter weights.

## 2.2 M-ary Bi-Orthogonal Keying (MBOK)

Ten different performance curves are presented for the 5.5 Mbps MBOK modulation scheme. The first four plots present current performance with no equalizer being used. The next six plots present performance expectations when a sliding decision feedback equalizer is incorporated. All plots with the sliding DFE were done with only 2 feed-forward taps. There are a pair of plots showing the performance of the sliding DFE with 5, 10, and 20 feed-back taps respectively.

### 2.2.1 Performance Without Equalizer

The current unequalized receiver is a very low cost, very low complexity solution to the multipath problem. The limiting IF receiver and shared transmit/receive Butterworth and SAW filters provide an implementation that performs admirable in the benign office environment.

The bit error rate curve for unequalized MBOK shown in Figure 2.2 is included to emphasize that the simulation data provided here is grounded in reality. The performance of the Butterworth and SAW transmit/receive filters near the 10 percent packet error rate is approximately 1dB worse than the ideal 50% root raised cosine matched filters. Keep this in mind when attempting to compare result presented here with those found elsewhere. As expected, the bit error rate curves for the MBOK waveform agree with the bit error rate curves for the QMBOK waveform shown later.

The unequalized packet error rate in thermal noise only is presented in Figure 2.3 for both 64 byte packets and 1000 byte packets. Again, a similar set of curves is also presented for the 50% root raised cosine ideal matched filters. The same 1dB performance degradation from using the Butterworth and SAW filters is visible for both packet lengths when compared against the ideal matched filters. The two points of interest are the Eb/No values for 10 percent packet error rates on the corresponding Butterworth/SAW curves. For packet lengths of 64 bytes, this point is at Eb/No=6.6dB. For packet lengths of 1000 bytes, this point is at Eb/No=8.1dB. As expected, the packet error rate curves for the MBOK waveform agree with the packet error rate curves for the QMBOK waveform shown later.

The unequalized packet error rate in multipath only is presented in Figure 2.4 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=62nsec. For packet lengths of 1000 bytes, this point is at Trms=61nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The unequalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.5 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=18dB. For packet lengths of 1000 bytes, this point is at Eb/No=22dB.

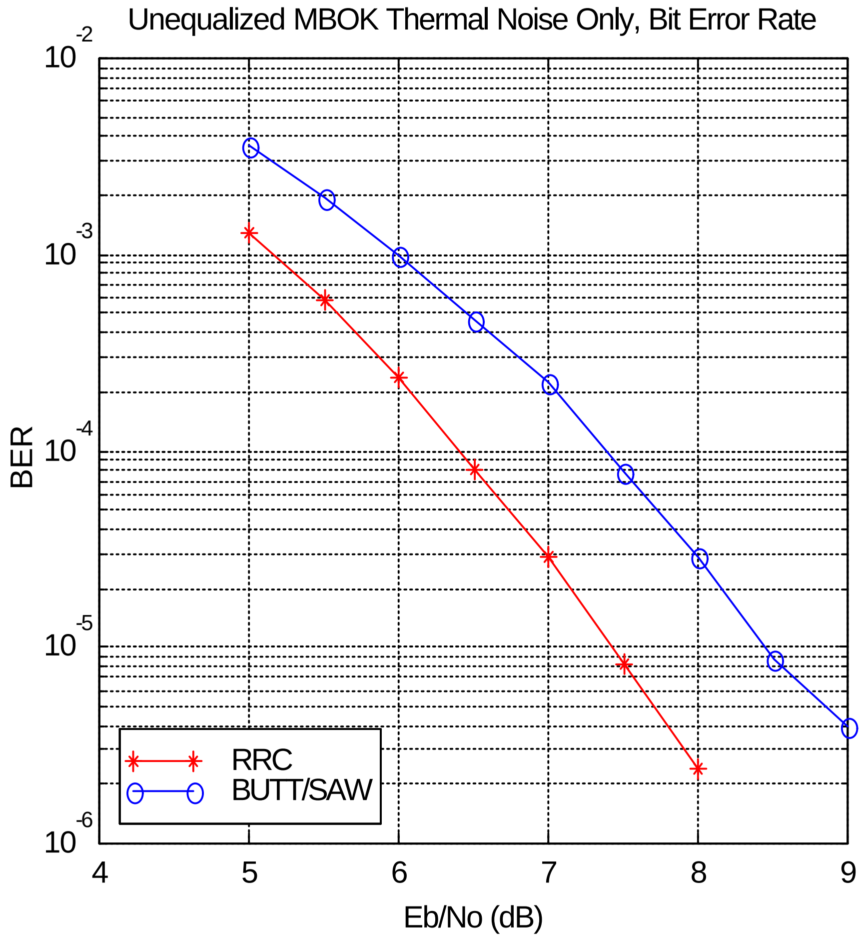


**Figure 2.2 - Unequalized MBOK thermal noise only, BER**

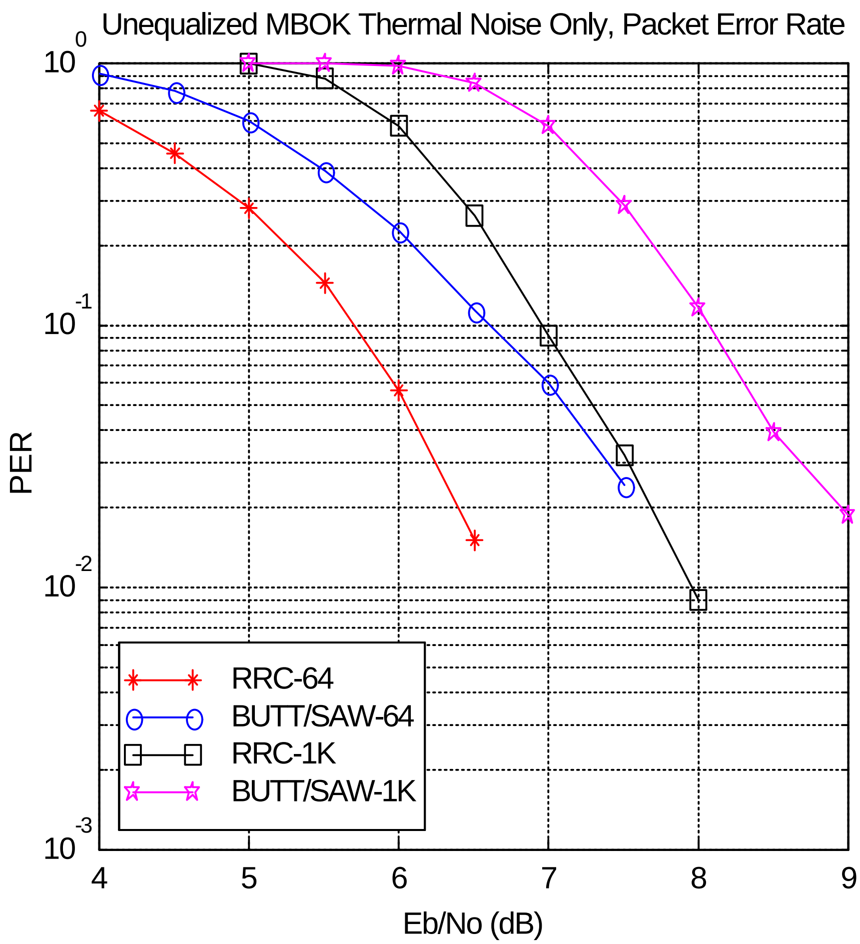


**Figure 2.3 - Unequalized MBOK thermal noise only, PER**

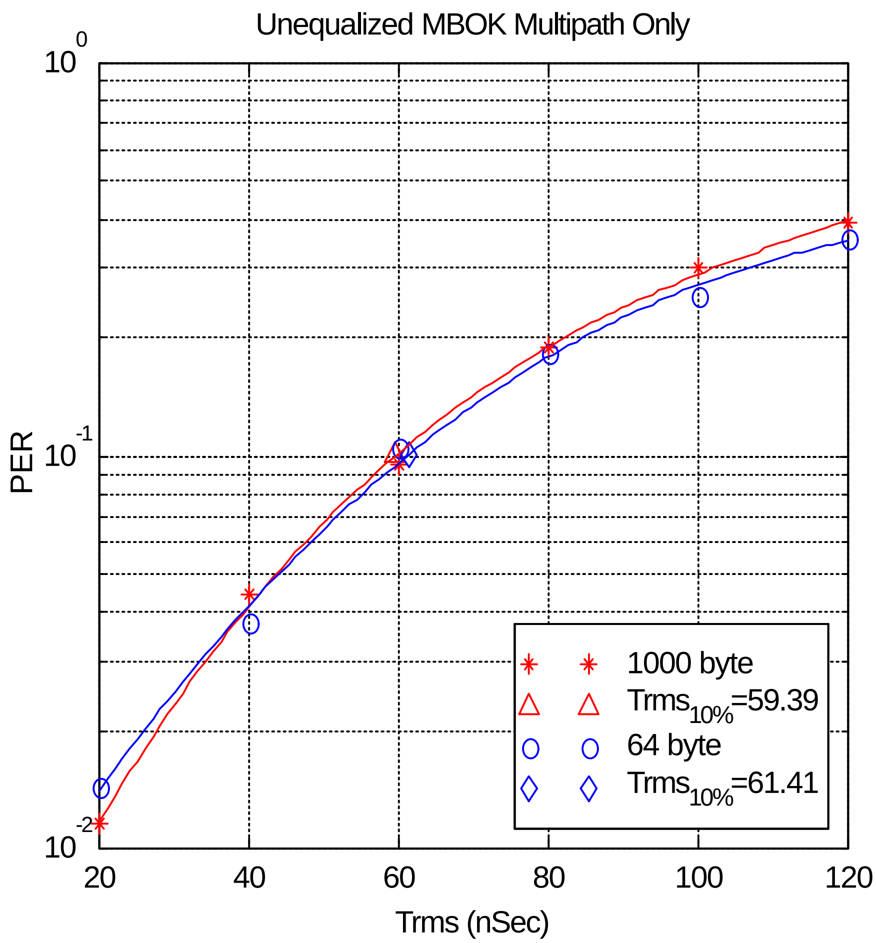


**Figure 2.4 - Unequalized MBOK multipath only**

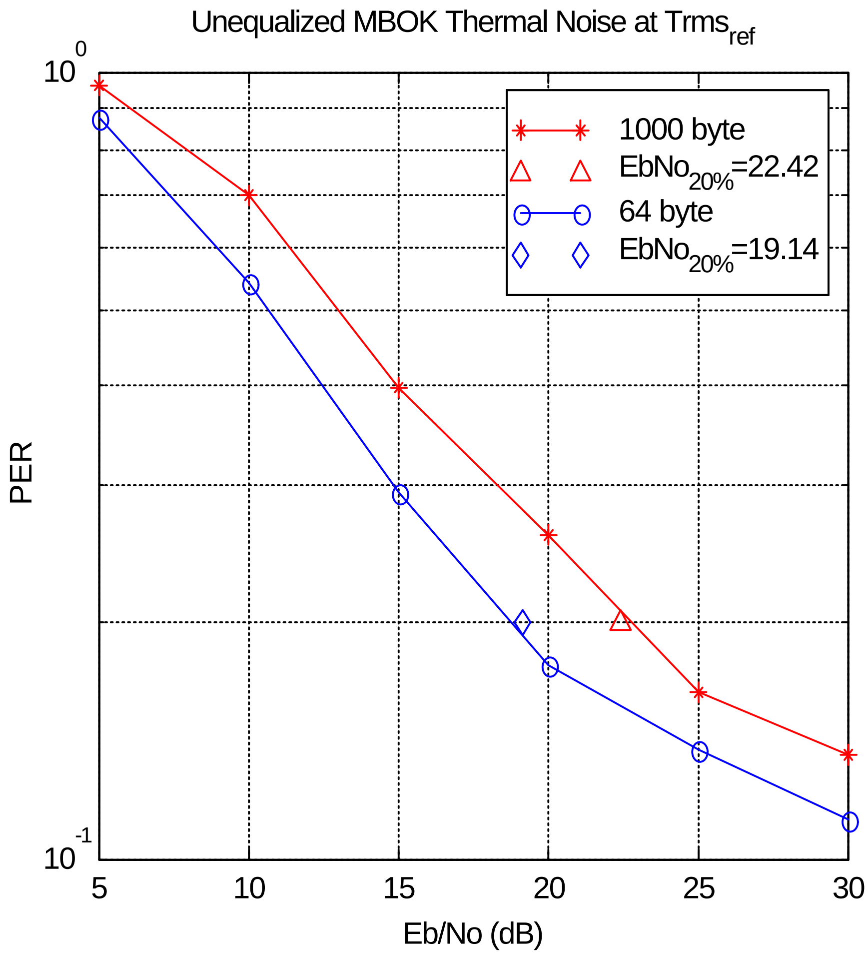


**Figure 2.5 - Unequalized MBOK thermal noise at $Trms_{ref}$**

### 2.2.2 Performance With Equalizer

As with the unequalized solution, the sliding decision feedback equalizer is also very low cost with low complexity. The equalizer begins to show performance that encompasses a wider range of multipath environments. Consider just 2 feed-forward taps and 10 feed-back taps. The feed-forward complexity is two full complex multiplies and one complex addition. The feed-back complexity reduces to 10 complex adds or subtracts. Include one more complex subtraction and a hard decision to complete the equalizer.

Bit error rate and packet error rate curves were not run for the equalized case since they will be essentially the same as the unequalized case shown before. The packet error rate in multipath only and the packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value are presented below for equalizers using 5, 10, and 20 feedback taps. Only the Butterworth and SAW combination transmit/receive filters were used in preparing the equalized performance curves.

#### 2.2.2.1 Sliding DFE (2 feed-forward taps, 5 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and five feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.6 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=138nsec. For packet lengths of 1000 bytes, this point is at Trms=134nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The equalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.7 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=19dB. For packet lengths of 1000 bytes, this point is at Eb/No=24dB.

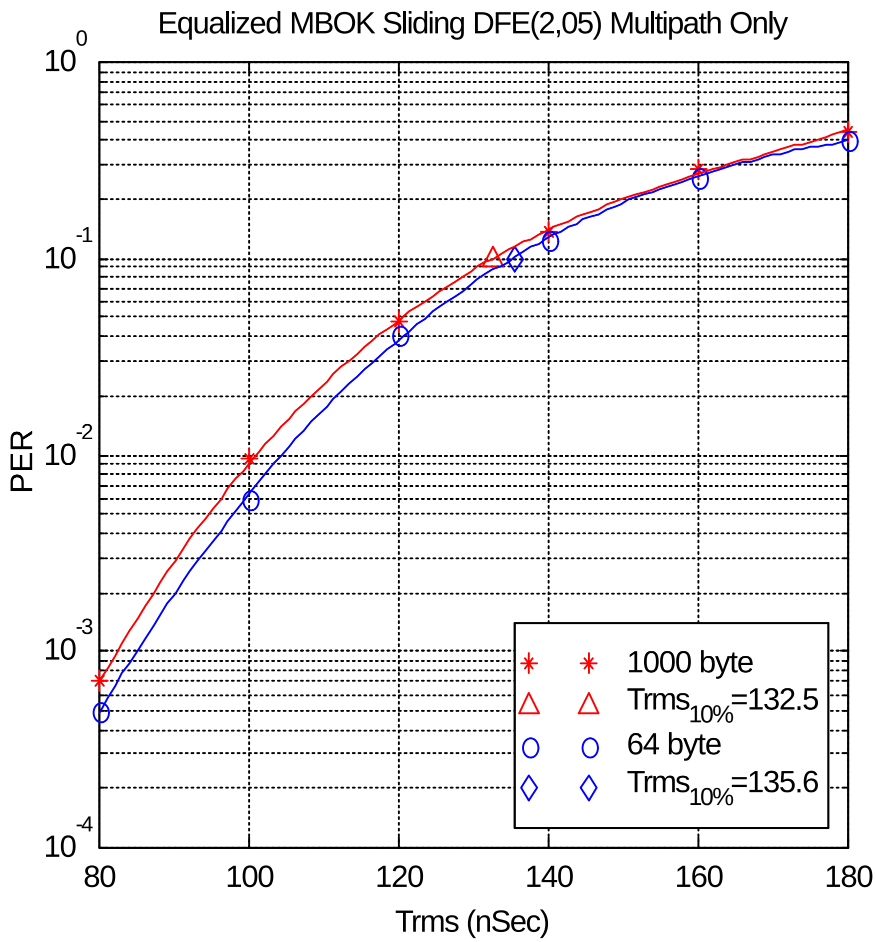


**Figure 2.6 - Equalized MBOK sliding DFE(2,05) multipath only**

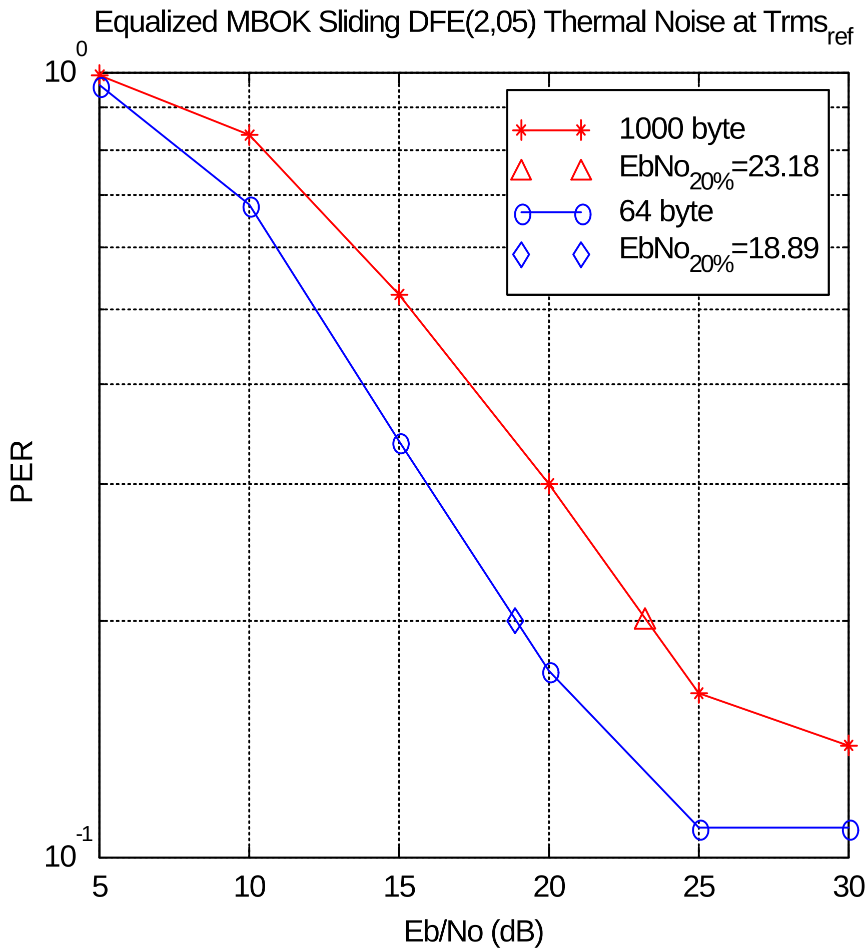


**Figure 2.7 - Equalized MBOK sliding DFE(2,05) thermal noise at Trms$_{ref}$**

### 2.2.2.2 Sliding DFE (2 feed-forward taps, 10 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and ten feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.8 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=227nsec. For packet lengths of 1000 bytes, this point is at Trms=225nsec. These two values are referred to later as the reference rms delay spread Trms$_{ref}$.

The equalized packet error rate with thermal noise and multipath set at the Trms$_{ref}$ value determined above is presented in Figure 2.9 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of Trms$_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=21dB. For packet lengths of 1000 bytes, this point is at Eb/No=26dB.

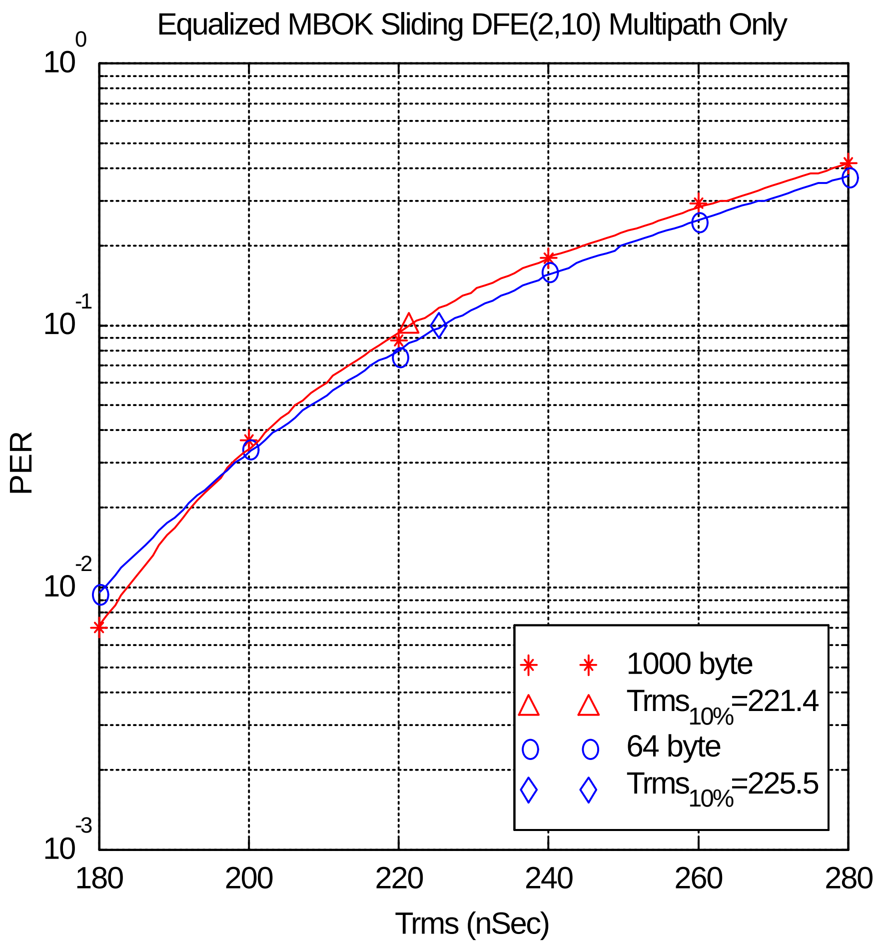


**Figure 2.8 - Equalized MBOK sliding DFE(2,10) multipath only**

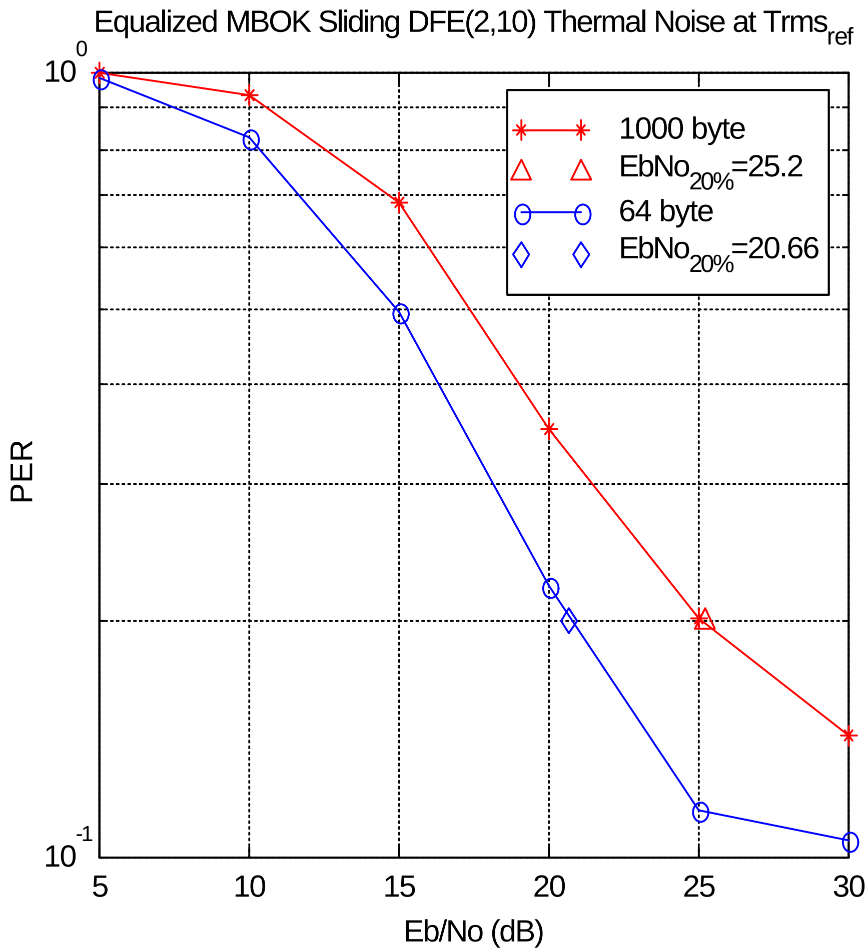


**Figure 2.9 - Equalized MBOK sliding DFE(2,10) thermal noise at $Trms_{ref}$**

### 2.2.2.3 Sliding DFE (2 feed-forward taps, 20 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and twenty feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.10 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=390nsec. For packet lengths of 1000 bytes, this point is at Trms=381nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The equalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.11 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=24dB. For packet lengths of 1000 bytes, this point is at Eb/No=28dB.

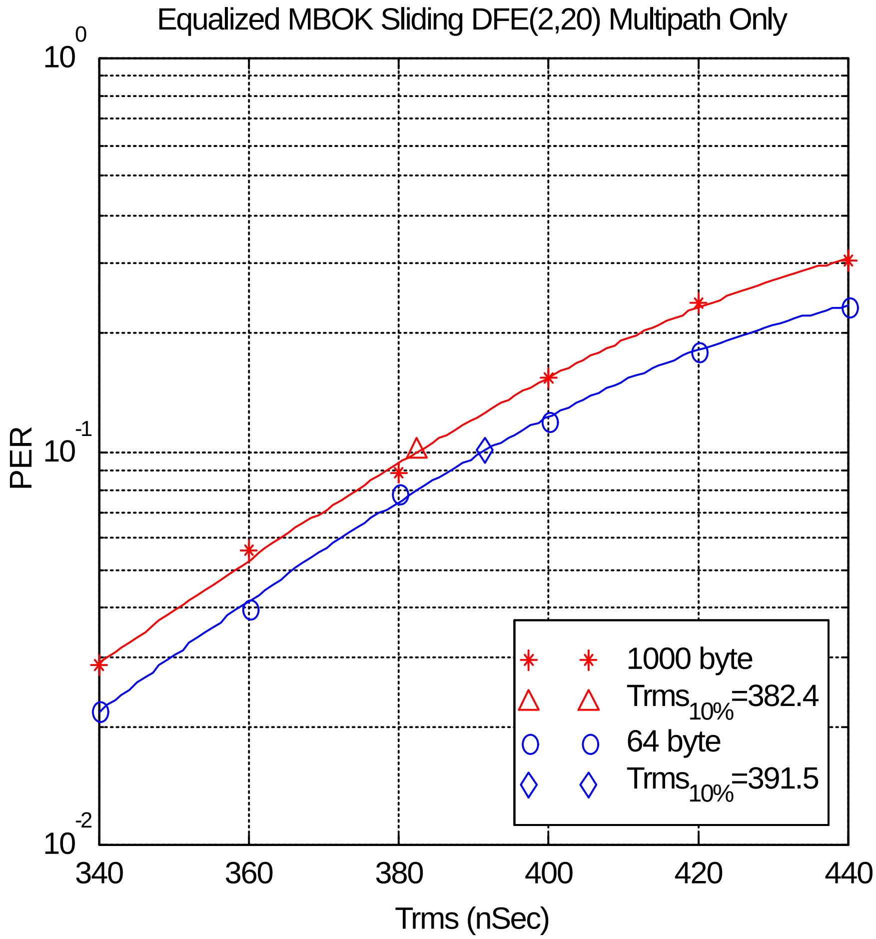


**Figure 2.10 - Equalized MBOK sliding DFE(2,20) multipath only**

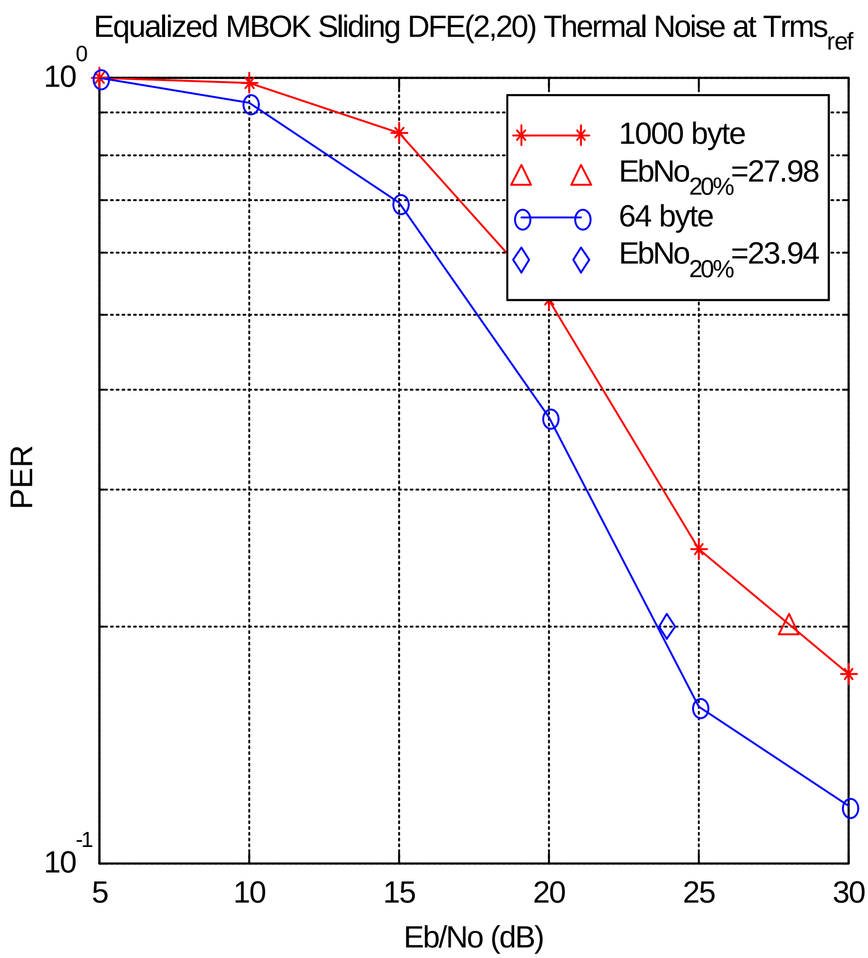


**Figure 2.11 - Equalized MBOK sliding DFE(2,20) thermal noise at $Trms_{ref}$**

## 2.3 Quadrature M-ary Bi-Orthogonal Keying (QMBOK)

Ten different performance curves are presented for the 11 Mbps QMBOK modulation scheme. The first four plots present current performance with no equalizer being used. The next six plots present performance expectations when a sliding decision feedback equalizer is incorporated. All plots with the sliding DFE were done with only 2 feed-forward taps. There are a pair of plots showing the performance of the sliding DFE with 5, 10, and 20 feed-back taps respectively.

### 2.3.1 Performance Without Equalizer

The current unequalized receiver is a very low cost, very low complexity solution to the multipath problem. The limiting IF receiver and shared transmit/receive Butterworth and SAW filters provide an implementation that performs admirable in the benign office environment.

The bit error rate curve for unequalized QMBOK shown in Figure 2.12 is included to emphasize that the simulation data provided here is grounded in reality. The performance of the Butterworth and SAW transmit/receive filters near the 10 percent packet error rate is approximately 1dB worse than the ideal 50% root raised cosine matched filters. Keep this in mind when attempting to compare result presented here with those found elsewhere. As expected, the bit error rate curves for the QMBOK waveform agree with the bit error rate curves for the MBOK waveform shown earlier.

The unequalized packet error rate in thermal noise only is presented in Figure 2.13 for both 64 byte packets and 1000 byte packets. Again, a similar set of curves is also presented for the 50% root raised cosine ideal matched filters. The same 1dB performance degradation from using the Butterworth and SAW filters is visible for both packet lengths when compared against the ideal matched filters. The two points of interest are the Eb/No values for 10 percent packet error rates on the corresponding Butterworth/SAW curves. For packet lengths of 64 bytes, this point is at Eb/No=6.6dB. For packet lengths of 1000 bytes, this point is at Eb/No=8.1dB. As expected, the packet error rate curves for the QMBOK waveform agree with the packet error rate curves for the MBOK waveform shown earlier.

The unequalized packet error rate in multipath only is presented in Figure 2.14 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=22nsec. For packet lengths of 1000 bytes, this point is at Trms=20nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The unequalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.15 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=16dB. For packet lengths of 1000 bytes, this point is at Eb/No=19dB.

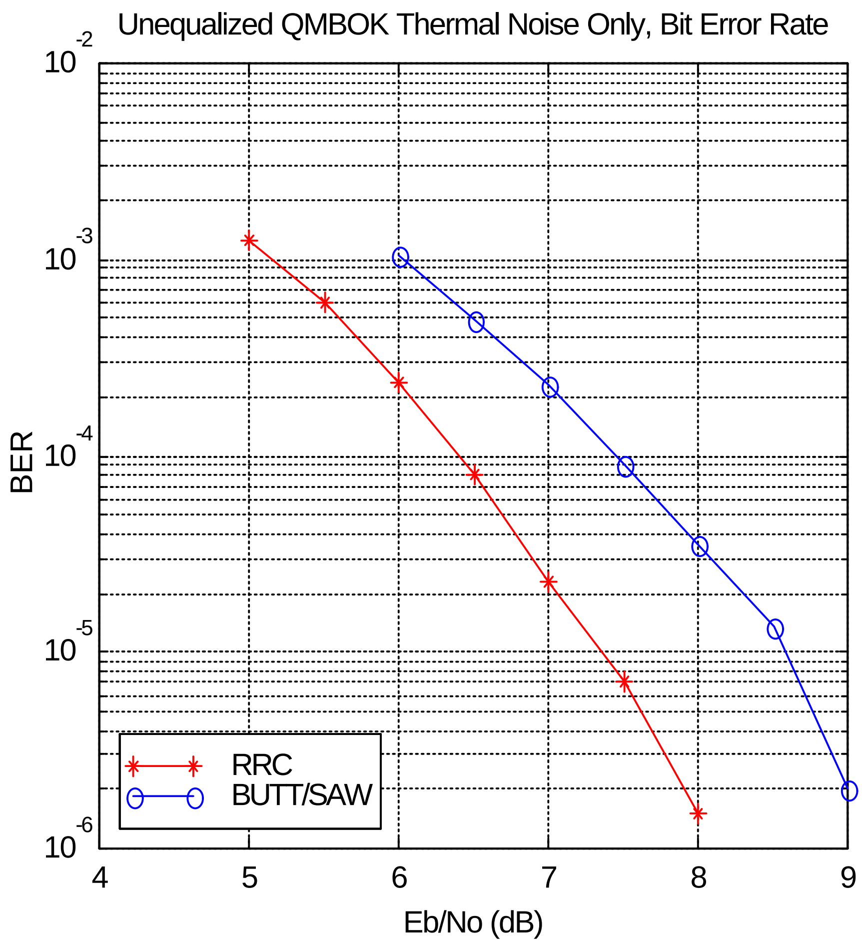


**Figure 2.12 - Unequalized QMBOK thermal noise only, BER**

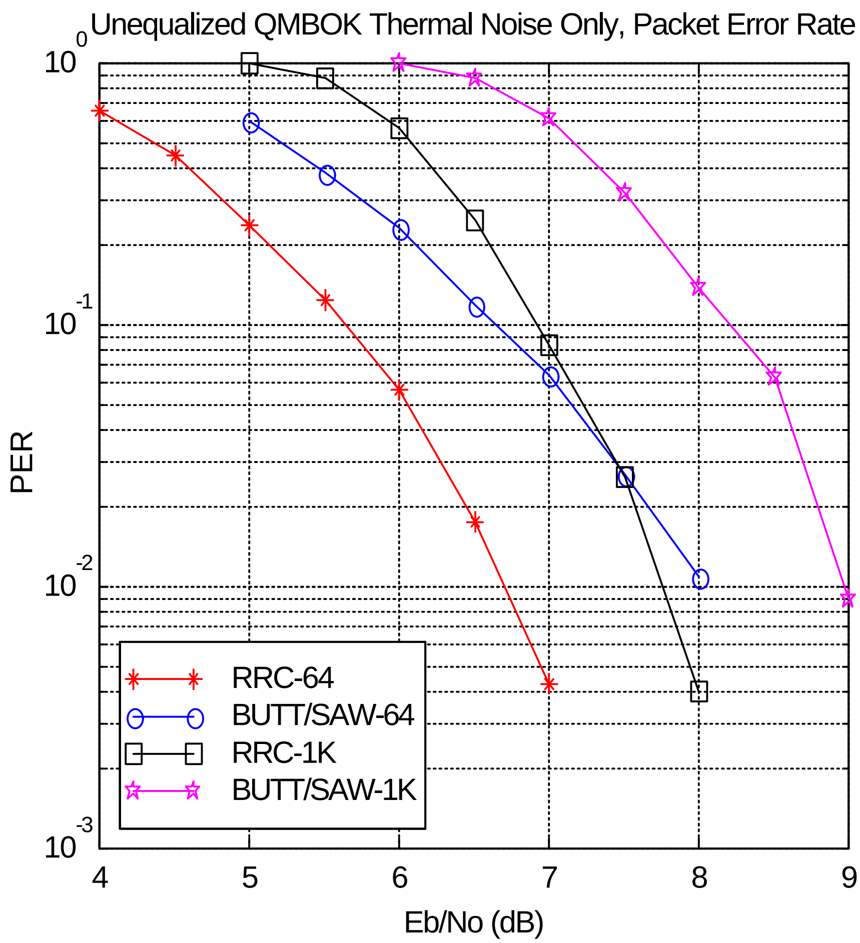


**Figure 2.13 - Unequalized QMBOK thermal noise only, PER**

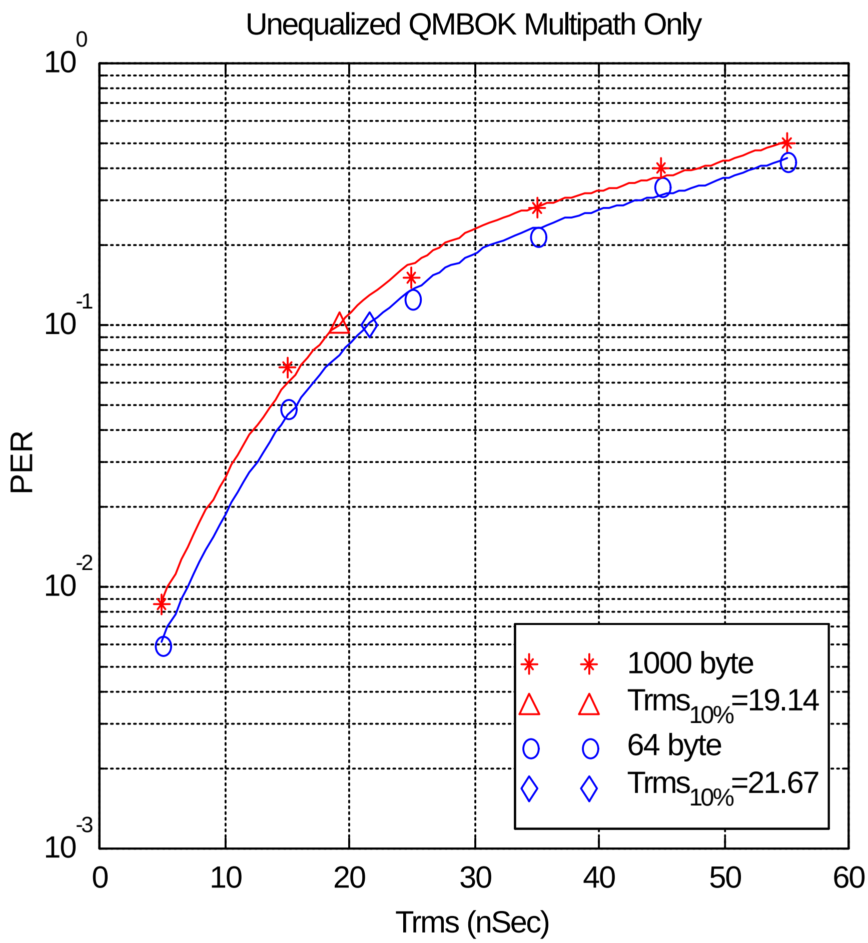


**Figure 2.14 - Unequalized QMBOK multipath only**

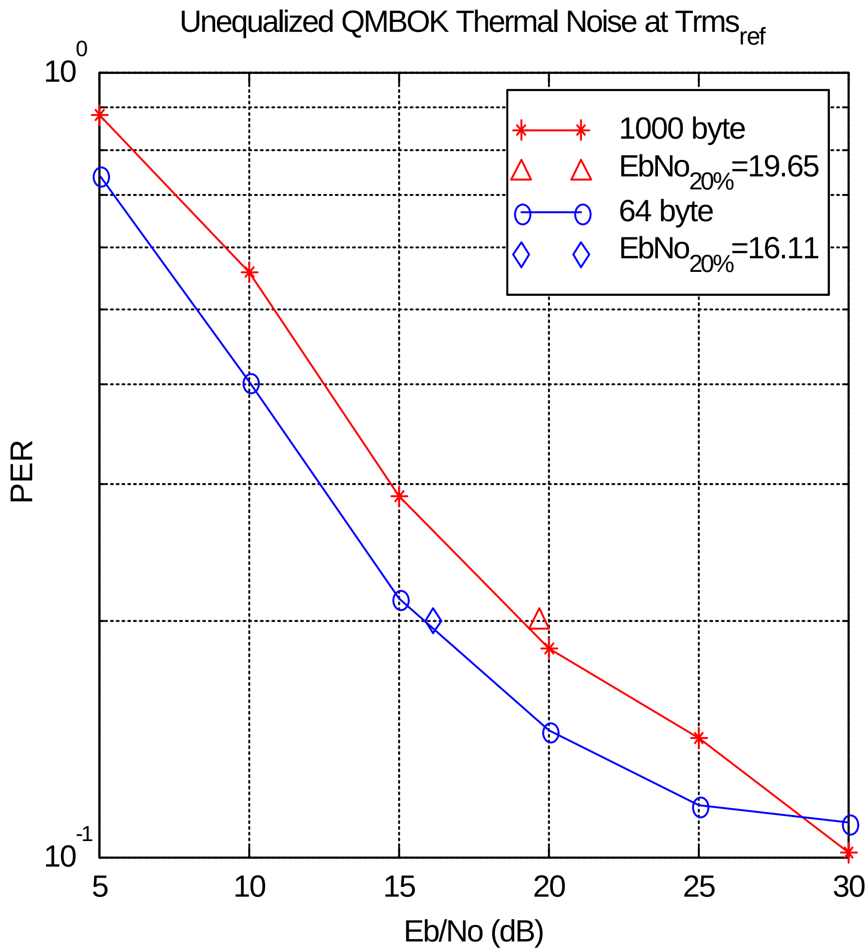


**Figure 2.15 - Unequalized QMBOK thermal noise at Trms$_{ref}$**

## 2.3.2 Performance With Equalizer

As with the unequalized solution, the sliding decision feedback equalizer is also very low cost with low complexity. The equalizer begins to show performance that encompasses a wider range of multipath environments. Consider just 2 feed-forward taps and 10 feed-back taps. The feed-forward complexity is two full complex multiplies and one complex addition. The feed-back complexity reduces to 10 complex adds or subtracts. Include one more complex subtraction and a hard decision to complete the equalizer.

Bit error rate and packet error rate curves were not run for the equalized case since they will be essentially the same as the unequalized case shown before. The packet error rate in multipath only and the packet error rate with thermal noise and multipath set at the Trms$_{ref}$ value are presented below for equalizers using 5, 10, and 20 feedback taps. Only the Butterworth and SAW combination transmit/receive filters were used in preparing the equalized performance curves.

### 2.3.2.1 Sliding DFE (2 feed-forward taps, 5 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and five feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.16 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=109nsec. For packet lengths of 1000 bytes, this point is at Trms=106nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The equalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.17 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=19dB. For packet lengths of 1000 bytes, this point is at Eb/No=23dB.

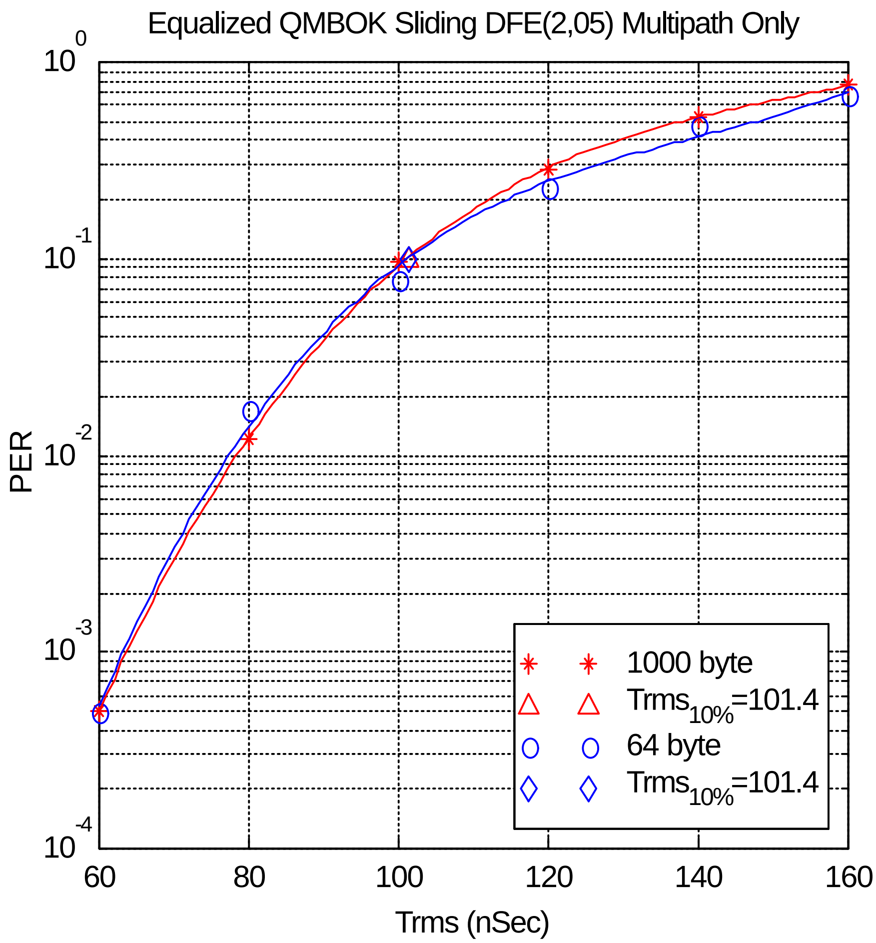


**Figure 2.16 - Equalized QMBOK sliding DFE(2,05) multipath only**

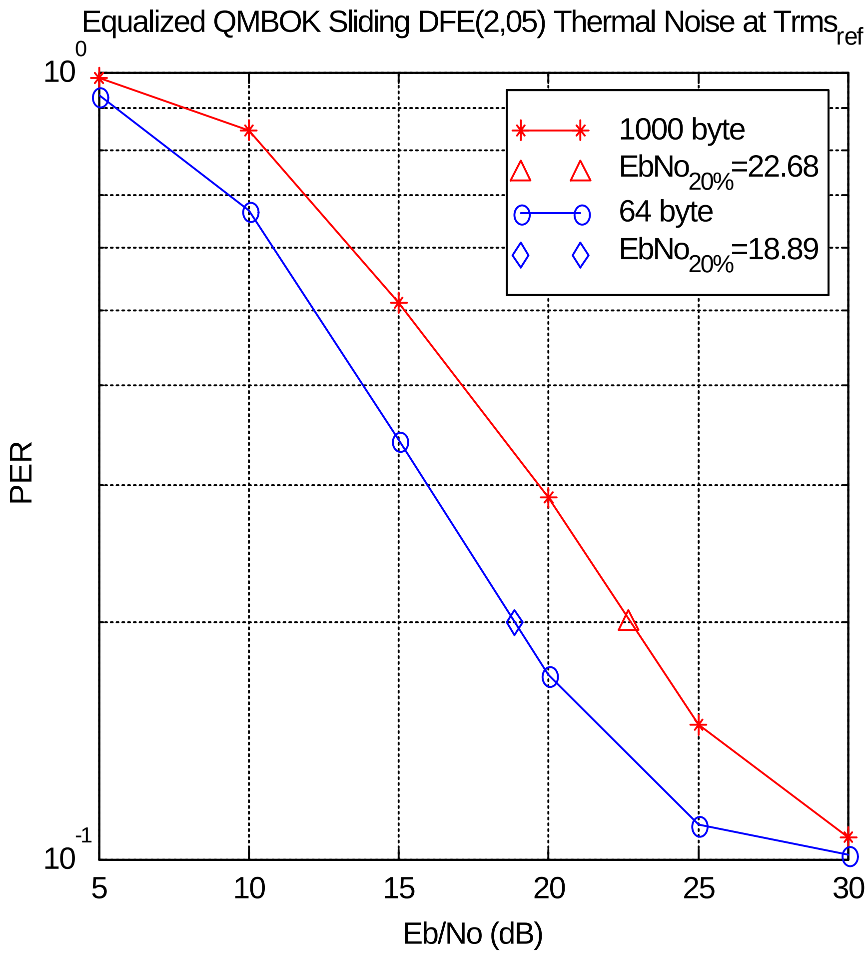


**Figure 2.17 - Equalized QMBOK sliding DFE(2,05) thermal noise at $Trms_{ref}$**

### 2.3.2.2 Sliding DFE (2 feed-forward taps, 10 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and ten feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.18 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=189nsec. For packet lengths of 1000 bytes, this point is at Trms=184nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.

The equalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.19 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=21.5dB. For packet lengths of 1000 bytes, this point is at Eb/No=24.5dB.

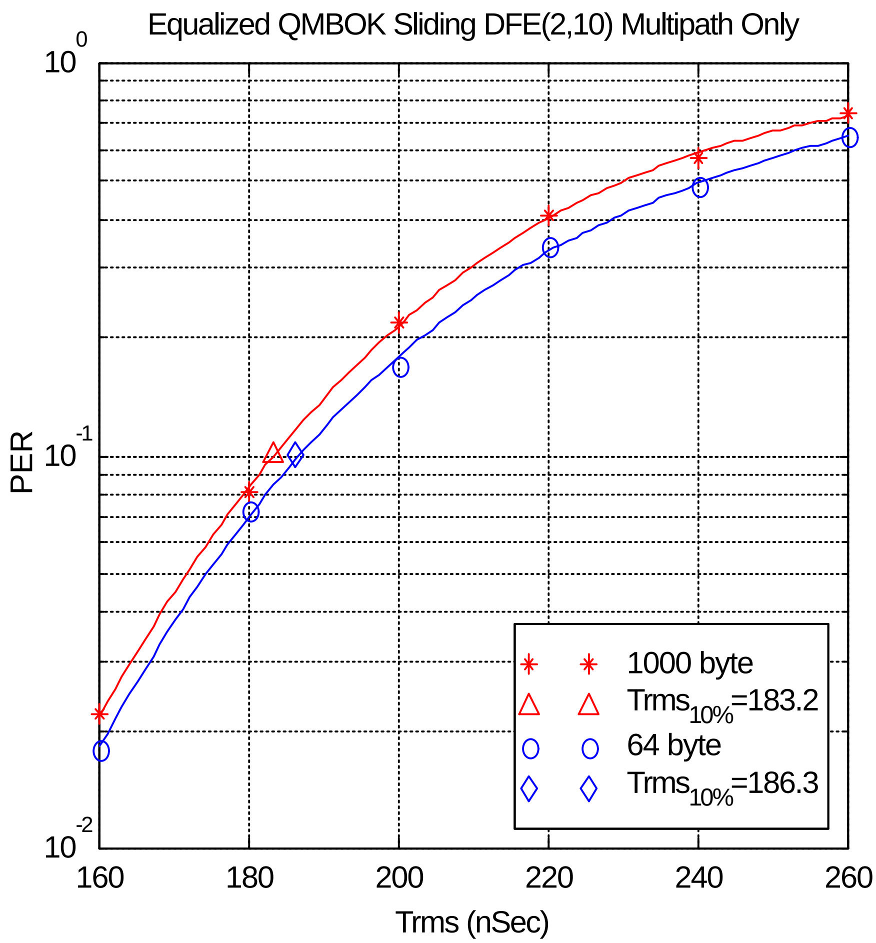


**Figure 2.18 - Equalized QMBOK sliding DFE(2,10) multipath only**

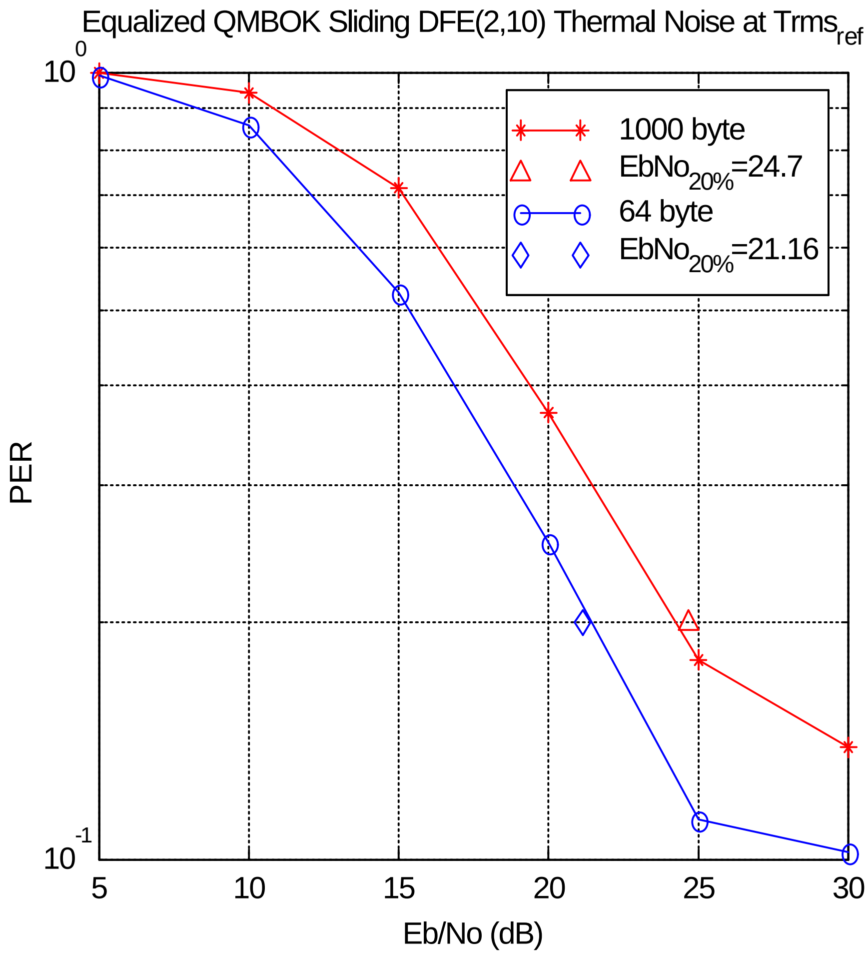


**Figure 2.19 - Equalized QMBOK sliding DFE(2,10) thermal noise at $Trms_{ref}$**

### 2.3.2.3 Sliding DFE (2 feed-forward taps, 20 feed-back taps)

A sliding decision feedback equalizer is now added to the simulation. This particular DFE has two feed-forward taps and twenty feed-back taps.

The equalized packet error rate in multipath only is presented in Figure 2.20 for both 64 byte packets and 1000 byte packets. The baseline exponentially decaying Rayleigh fading channel model was used in the simulation while varying the rms delay spread parameter. The two points of interest are the Trms values for 10 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Trms=339nsec. For packet lengths of 1000 bytes, this point is at Trms=325nsec. These two values are referred to later as the reference rms delay spread $Trms_{ref}$.
The equalized packet error rate with thermal noise and multipath set at the $Trms_{ref}$ value determined above is presented in Figure 2.21 for both 64 byte packets and 1000 byte packets. Again, the baseline exponentially decaying Rayleigh fading channel model was used in the simulation with a fixed rms delay spread of $Trms_{ref}$ while varying the Eb/No. The two points of interest are the Eb/No values for 20 percent packet error rates on the two curves. For packet lengths of 64 bytes, this point is at Eb/No=23.5dB. For packet lengths of 1000 bytes, this point is at Eb/No=27.5dB.

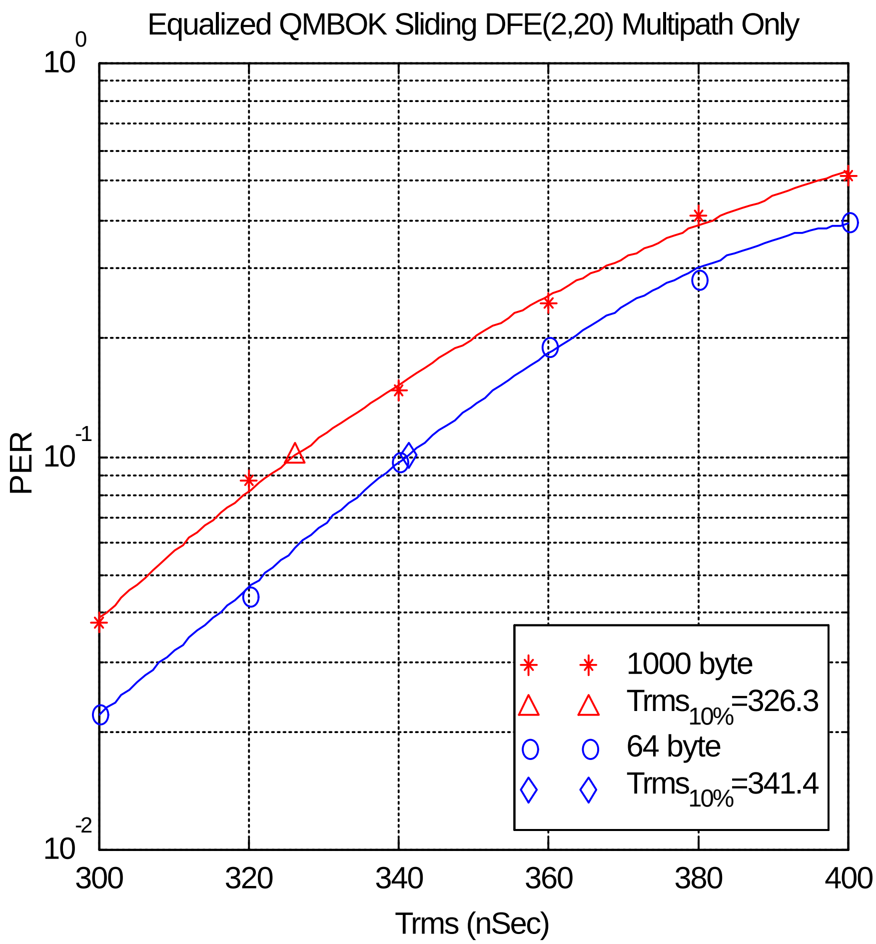


**Figure 2.20 - Equalized QMBOK sliding DFE(2,20) multipath only**

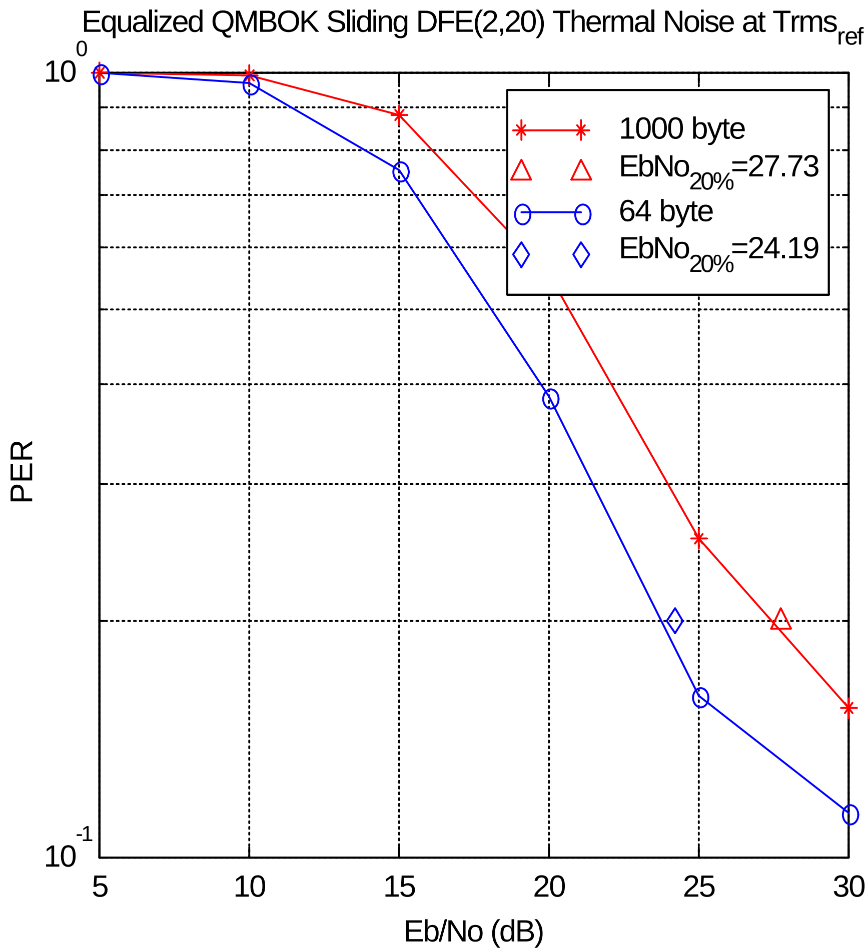


**Figure 2.21 - Equalized QMBOK sliding DFE(2,20) thermal noise at $Trms_{ref}$**

## 2.4 Summary of Results

A summary of results is presented in Table 2.1 where the points of interest for the previous graphs are shown.

| | 5.5 Mbit/s - MBOK | 11 Mbit/s - QMBOK |
|---|---|---|
| **Unequalized** | | |
| Eb/No at PER=10%, AWGN, 64b | 6.6 dB | 6.6 dB |
| Trms at PER=10%, noise free, 64b | 61 nsec | 22 nsec |
| Eb/No at PER=20%, with Trms at 10%, 64b | 19.1 dB | 16.1 dB |
| Eb/No at PER=10%, AWGN, 1000b | 8.1 dB | 8.2 dB |
| Trms at PER=10%, noise free, 1000b | 59 nsec | 19 nsec |
| Eb/No at PER=20%, with Trms at 10%, 1000b | 22.4 dB | 19.7 dB |
| **Equalized Sliding DFE nFF=2, nFB=5** | | |
| Trms at PER=10%, noise free, 64b | 136 nsec | 101 nsec |
| Eb/No at PER=20%, with Trms at 10%, 64b | 18.9 dB | 18.9 dB |
| Trms at PER=10%, noise free, 1000b | 133 nsec | 101 nsec |
| Eb/No at PER=20%, with Trms at 10%, 1000b | 23.2 dB | 22.7 dB |
| **Equalized Sliding DFE nFF=2, nFB=10** | | |
| Trms at PER=10%, noise free, 64b | 226 nsec | 186 nsec |
| Eb/No at PER=20%, with Trms at 10%, 64b | 20.7 dB | 21.2 dB |
| Trms at PER=10%, noise free, 1000b | 221 nsec | 183 nsec |
| Eb/No at PER=20%, with Trms at 10%, 1000b | 25.2 dB | 24.7 dB |
| **Equalized Sliding DFE nFF=2, nFB=20** | | |
| Trms at PER=10%, noise free, 64b | 392 nsec | 341 nsec |
| Eb/No at PER=20%, with Trms at 10%, 64b | 24 dB | 24.2 dB |
| Trms at PER=10%, noise free, 1000b | 382 nsec | 326 nsec |
| Eb/No at PER=20%, with Trms at 10%, 1000b | 28 dB | 27.7 dB |

**Table 2.1 - Summary of performance results**

# 3. Sliding MLSE/DFE Performance

This section presents estimated performance one would obtain by using a 2-tap MLSE (16 state) in combination with the FB taps. This eliminates the FF DFE taps. It is estimated the 2-tap MLSE will provide about at least a 3 dB gain in multipath/thermal performance over what is above. It is hoped detailed simulations can be provided at a later date.

| Sliding MLSE/DFE 16 state, nFB=10 | 5.5 Mbit/s - MBOK | 11 Mbit/s - QMBOK |
|---|---|---|
| Trms at PER=10%, noise free, 64b | 226 nsec | 186 nsec |
| Eb/No at PER=20%, with Trms at 10%, 64b | 17.7 dB | 18.2 dB |
| Trms at PER=10%, noise free, 1000b | 221 nsec | 183 nsec |
| Eb/No at PER=20%, with Trms at 10%, 1000b | 22.2 dB | 21.7 dB |

## REFERENCES

[1] Carl Andren (HARRIS), “2.4 GHz High Rate PHY - Full Text,” doc:IEEE P802.11-98/47, January 1998.