CHAPTER SIX

RESULTS

In this chapter, all theoretical as well as simulation results described in *Chapters 2* to *5* are presented. In more detail, this chapter is structured as follows: In *Section 6.1* performance results of the DSSTS scheme in Rayleigh as well as Rician fading conditions are presented. Further, performance results of a Rayleigh vs. Rician fading environment are also presented here. The results of the SSTD scheme is not presented in this study, but can be obtained in [19, 20]. Lastly, in *Section 6.2*, the capacity CCDFs for the DSSTS scheme are presented.

Following a similar approach as in [17], the performance evaluation platform was implemented in C++ using an Object Orientated Programming (OOP) approach. The C++ code was compiled using *Intel*'s *ICC* and *GNU*'s *G++* compilers for *Linux* platforms. The BER performance results presented in *Section 6.1* were obtained by distributing the processor load of the simulation software over multiple workstations in the *University of Pretoria*'s *I-percube*, donated by *Intel*. The *I-percube* consists of 16 2.4GHz *Pentium 4* stations, each station running a *Mandrake Linux* operating system. The 16 stations are interconnected via *Fast Ethernet* connections, where process migration and message handling between the stations are managed transparently by *Open Mosix* for *Linux*. By using the I-percube, BER performance results that are usually time consuming, are obtained in a much faster fashion.

6.1 DSSTS RESULTS

The BER performance results of the DSSTS scheme's 2 to 10 antenna scenarios are presented in the following subsections for different channel parameters and environmental conditions. The simulation results were obtained by using the performance evaluation platform shown in *Chapter 5*, *Figure 5.4*. In all the BER performance graphs, the theoretical BER of a flat fading Rayleigh channel, as well as the theoretical BER of an AWGN channel is included as baseline reference to the performance of the proposed new DSSTS schemes. The theoretical derived BER of Alamouti's 2 antenna scenario is also included as reference against which subsequent DSSTS results will be benchmarked. The following assumptions were made during the evaluation of the DSSTS scheme:

- The total transmit power emanating from all of the DSSTS's different antenna scenarios equals the transmit power from a single transmit antenna scenario, i.e., perfect power conservation is assumed and unity power is transmitted in all cases.
- The fading amplitudes from each transmit antenna to the single receive antenna are mutually uncorrelated and Rayleigh or Rician distributed. In the case of the Rician distributed fading amplitudes, a LOS component of 6dB was added. See *Chapter 4*, *Section 4.1*.

Further assumptions include:

- The average powers received from each transmit antenna are the same at the receive antenna.
- The receiver has perfect knowledge of the channel, i.e. perfect CSI is assumed.

6.1.1 Performance results in a Rayleigh fading environment

Increasing the DSSTS scheme's number of antennas for a single user, directly effects it's BER performance. In order to show the effect of increasing the number of antennas for a single user on the BER performance of the DSSTS scheme in a Rayleigh fading environment (K = -100dB), the graphs are plotted at similar Doppler frequencies, i.e. 33Hz, 66Hz, and 100Hz, respectively. The simulation platform presented in *Chapter 5, Section 5.1.6* were used to simulate these effects and presented in *Figure 6.1, Figure 6.2,* and *Figure 6.3,* respectively.

From these figures the following general observations can be made:

- Improved BER performances of 7.5dB to 9dB are obtained by incorporating temporal (DS-SS) spreading into Alamouti's orthogonal ST coding scheme.
- A further improvement in BER performance of up to 2dB is obtained by increasing the number of transmit antennas. This improvement can be mainly attributed to transmit antenna diversity gain, i.e. the exploitation of additional space diversity.
- The 10 DSSTS antenna scheme performed the best and within 4dB of the AWGN channel scenario.

From *Figure 6.1,* i.e. with a Doppler frequency of 33Hz, the following important observations can be made:

- The DSSTS's 2 transmit antenna scenario obtained a 7.5dB gain over Alamouti's original 2 transmit antenna scheme.
- The DSSTS's 10 transmit antenna scenario performed the best; a 9.5dB gain is obtained at a BER of 10^{-4} over Alamouti's original 2 transmit antenna scheme. Note that it performed within 4dB of the AWGN channel scenario.

  The best performance gain between the different DSSTS schemes was obtained between the DSSTS's 2 transmit and 4 transmit antenna scenarios. A performance gain of 1dB is obtained at a BER of 10^{-4}. Smaller performance gains are obtained as the number of transmit antennas increase. This can be attributed to multi antenna interference as a result of the receiver's cross correlation between different spreading sequences not being perfect, as described in *Chapter 5, Section 5.1.4*. As the number of transmit antennas increase, the level of non-perfect cross-correlation interference increases and less gain is obtained.

- The DSSTS's 10 transmit antenna scenario only obtained a 2dB gain over the DSSTS's 2 transmit antennas scenario.

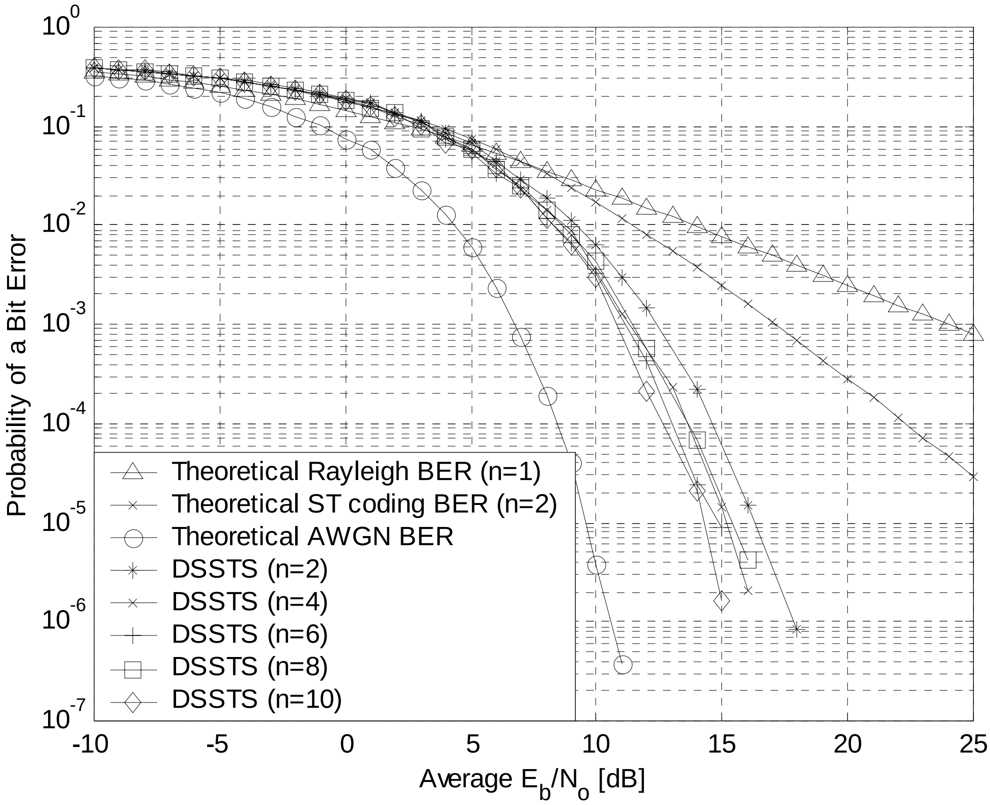

Figure 6.1. Single user performance evaluation for the DSSTS's 2 to 10 antennas scenario in a Rayleigh fading environment for f_d = 33Hz.

From *Figures 6.2* and *6.3* (i.e. with Doppler frequencies of 66Hz and 100Hz respectively), the following important observations can be made:

- The DSSTS's 2 transmit antenna scenario obtained a 8.5dB gain over Alamouti's original 2 transmit antennas scheme.
- The DSSTS's 10 transmit antenna scenario performed the best; a 9.5dB gain is obtained at a BER of 10^{-4} over Alamouti's original 2 transmit antennas scheme.

- As was the case with a Doppler frequency of 33 Hz, increasing the number of transmit antennas in the DSSTS scheme from 2 to 4 produced the best performance gain. A performance gain of 1dB is obtained at a BER of 10^{-4}. Also note that smaller performance gains are obtained as the number of transmit antennas increases. This is merely due to non-perfect cross-correlation interference caused by the increasing number of codes allocated to individual transmit antennas.
- The DSSTS's 10 transmit antennas scenario only obtained a 1dB gain over the DSSTS's 2 transmit antennas scenario.
- Less than 0.1dB gain is obtained between the DSSTS's 4, 6, 8 and 10 antennas scenarios.

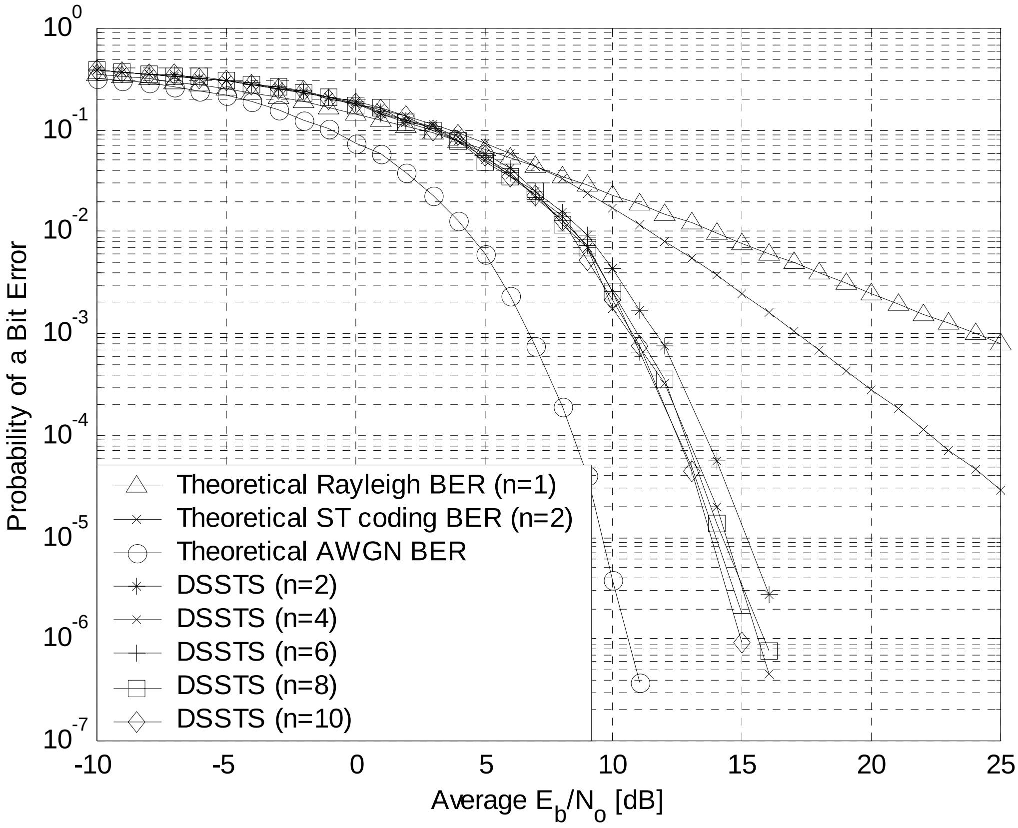

Figure 6.2. Single user performance evaluation for the DSSTS's 2 to 10 antennas scenario in a Rayleigh fading environment for f_d = 66Hz.

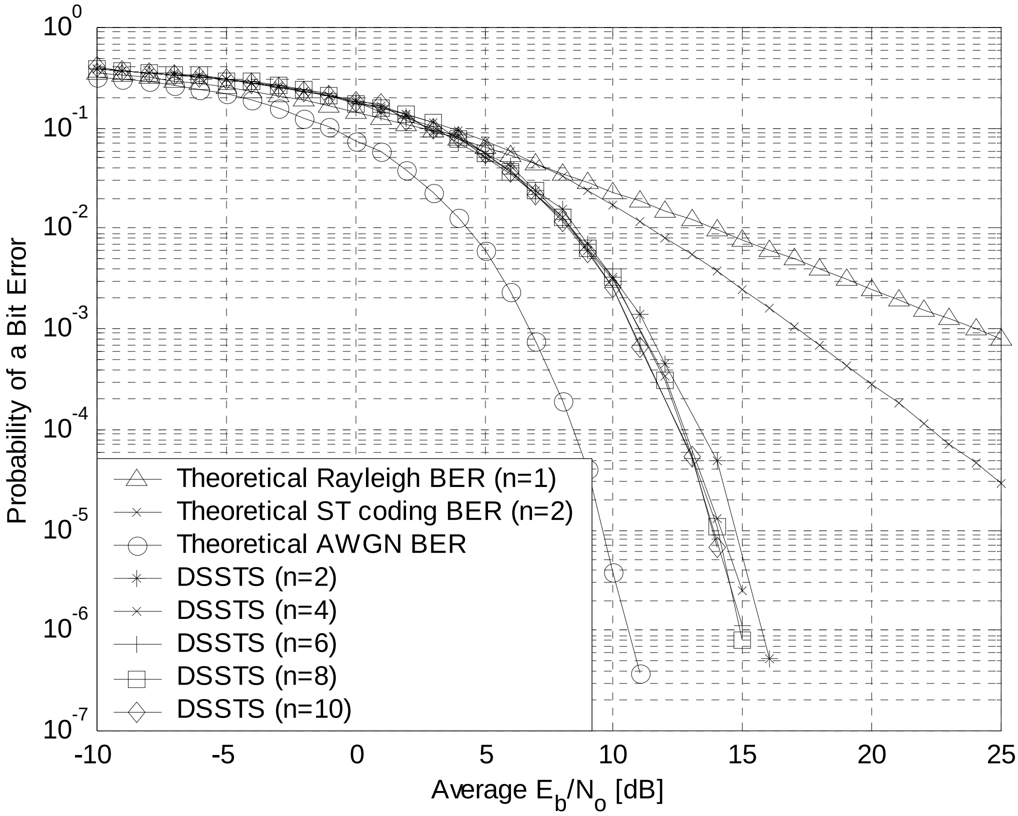

Figure 6.3. Single user performance evaluation for the DSSTS's 2 to 10 antennas scenarios in a Rayleigh fading environment with f_d = 100Hz.

In order to show the effect of the Doppler frequency on the BER performance of the DSSTS scheme in a Rayleigh fading environment (*K* = -100dB), the graphs are plotted for different Doppler frequencies with the number of transmit antennas held constant for each graph. These graphs are presented in *Figures 6.4, 6.5, 6.6, 6.7* and *6.8*. The following observations can be made:

- An improved BER performance is obtained for higher Doppler frequencies. This is mainly due to the fact that shorter error bursts occur, resulting in an improved BER performance. This performance gain is only at higher E_b/N_0, i.e. from 11dB upwards.
- With a Doppler frequency of 66Hz, a 1dB performance gain at a BER of 10^{-4} was obtained over the case where a Doppler frequency of 33Hz was used for the 2 transmit antennas scenario. However, a Doppler frequency of 100Hz only obtained a performance gain of 0.1dB over the 66Hz Doppler frequency case.

- Similar results are obtained for the 4, 6 and 8 antenna scenarios. In this case, a performance gain of 1dB is obtained at a BER of 10^{-4} with Doppler frequencies of 33Hz and 66Hz, where as no performance gain is obtained at Doppler frequencies of 66Hz and 100Hz.
- In the case of the DSSTS's 10 antennas scenario, no performance gains are obtained between different Doppler frequencies.

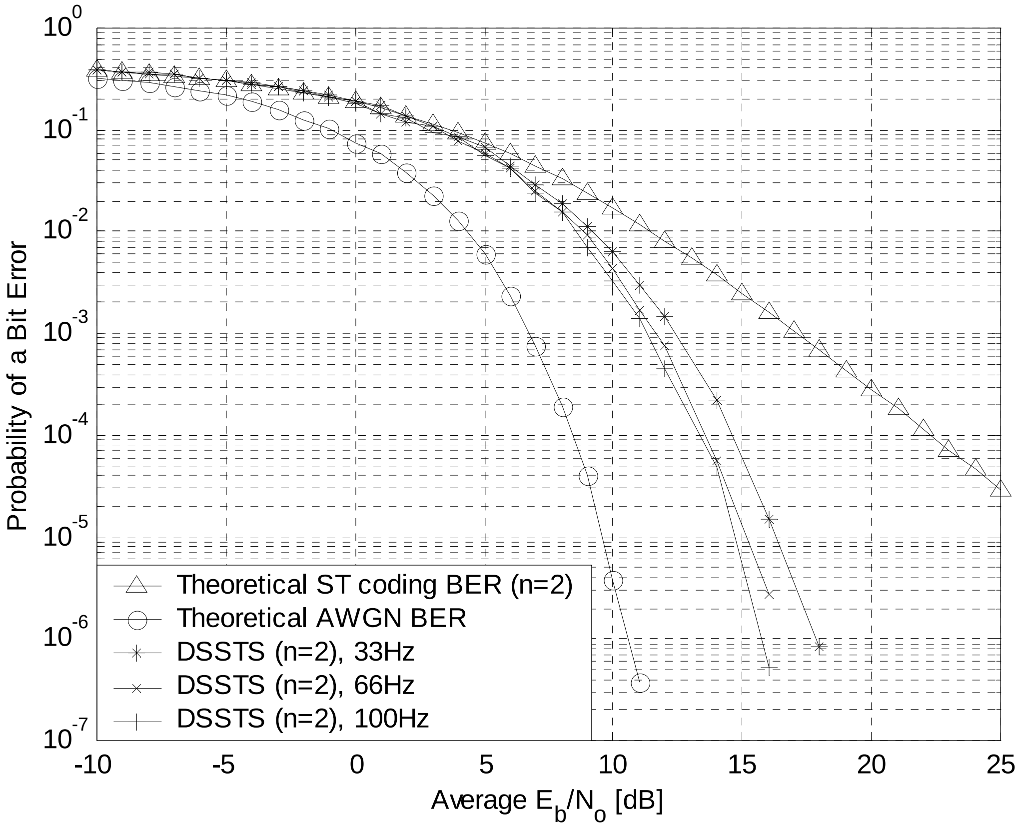

Figure 6.4. Single user performance evaluation for the DSSTS 2 antenna scheme in a Rayleigh fading environment for different Doppler frequencies.

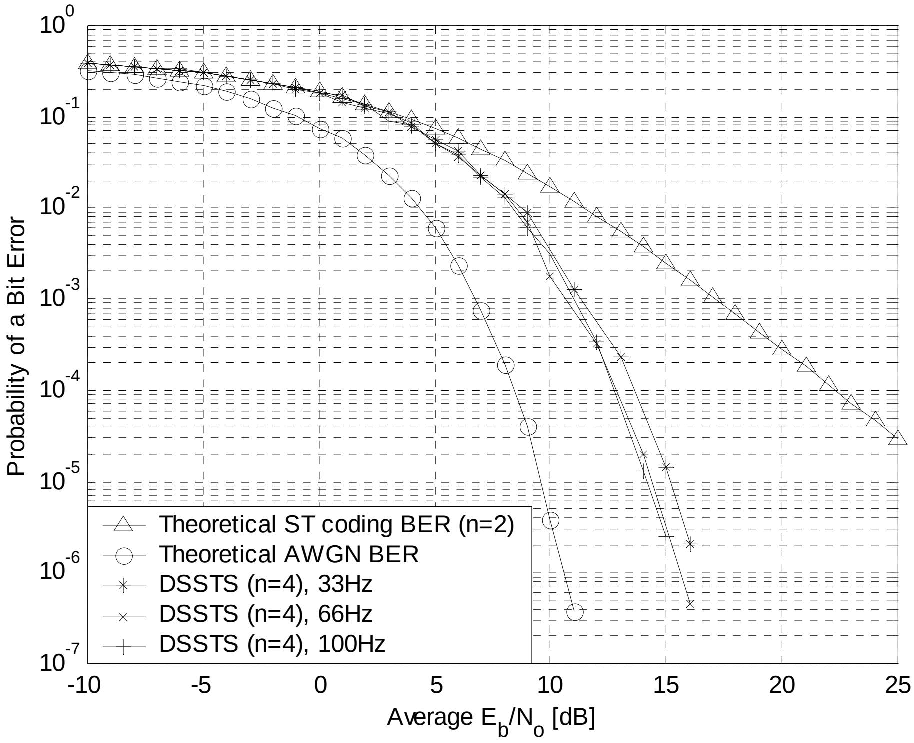

Figure 6.5. **Single user performance evaluation for the DSSTS 4 antenna scheme in a Rayleigh fading environment for different Doppler frequencies.**

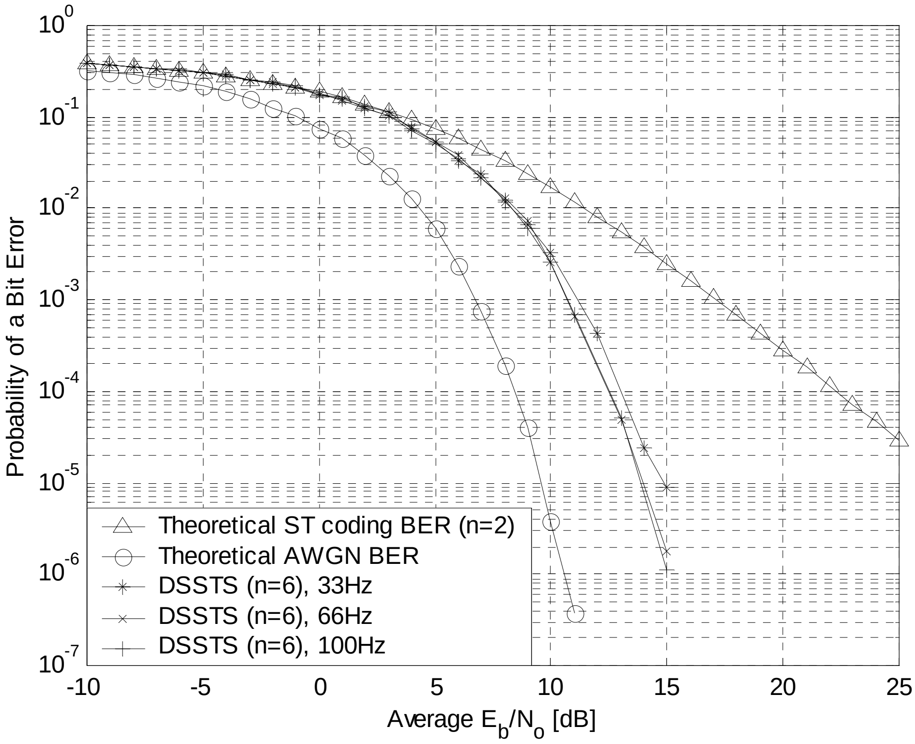

Figure 6.6. **Single user performance evaluation for the DSSTS 6 antenna scheme in a Rayleigh fading environment for different Doppler frequencies.**

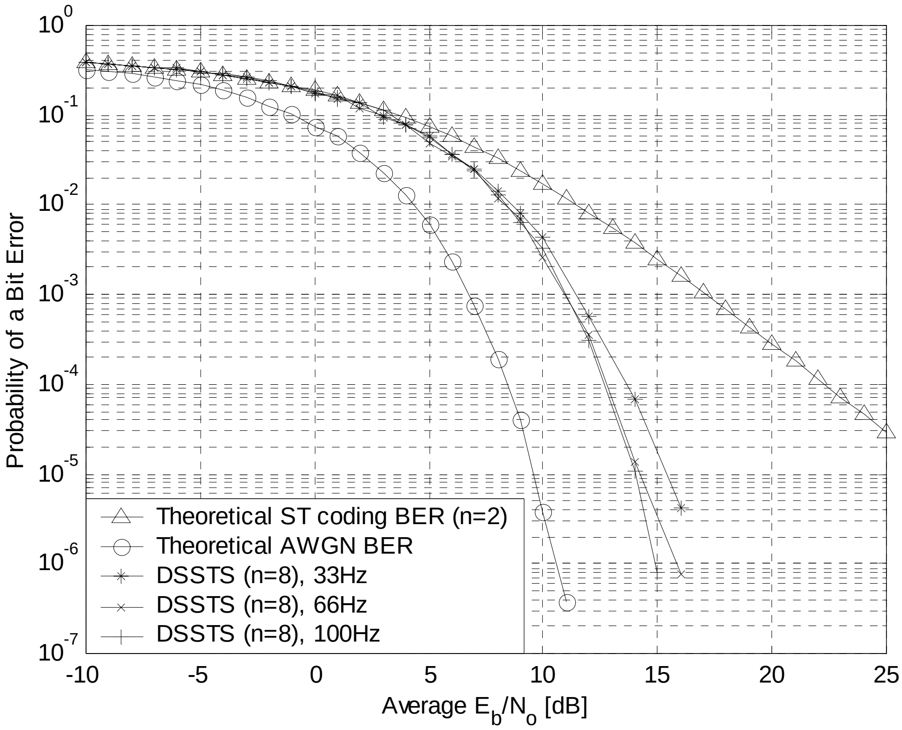

Figure 6.7. **Single user performance evaluation for the DSSTS 8 antenna scheme in a Rayleigh fading environment for different Doppler frequencies.**

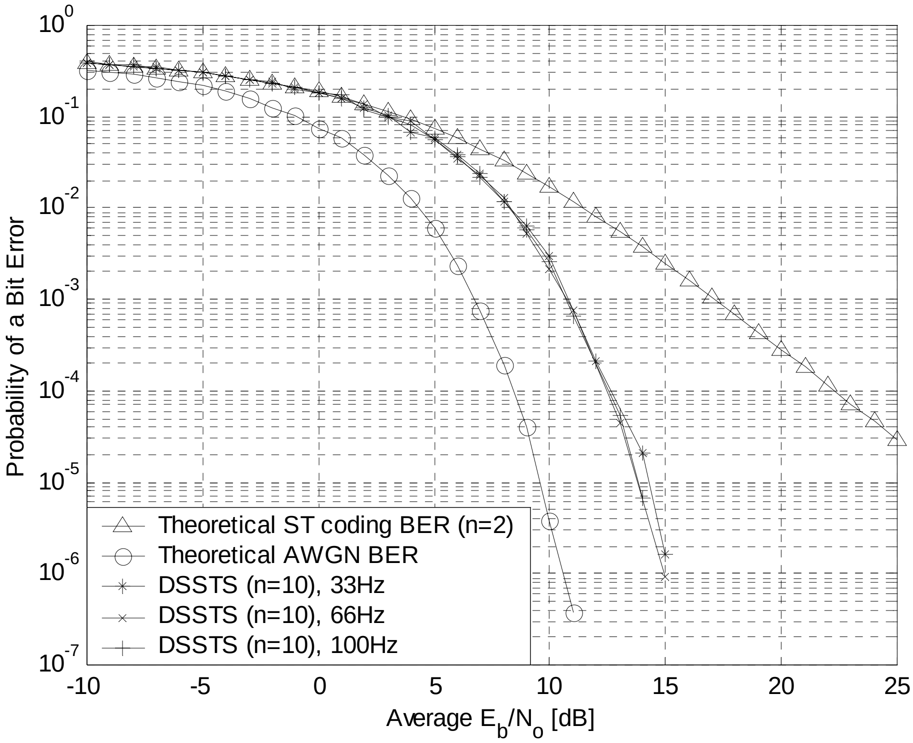

Figure 6.8. **Single user performance evaluation for the DSSTS 10 antenna scheme in a Rayleigh fading environment for different Doppler frequencies.**

6.1.2 Performance results in a Rician fading environment

In order to show the effect of increasing the DSSTS scheme's number of antennas on the BER performance of a single user in a Rician fading environment (K = 6dB), BER performance graphs were generated for similar Doppler frequencies, i.e. 33Hz, 66Hz, and 100Hz, respectively. The simulation platform presented in *Chapter 5, Section 5.1.6* were used to simulate these scenarios, presented in *Figure 6.9*, *Figure 6.10*, and *Figure 6.11*, respectively. From all of these figures the following general observations can be made:

- For a single user the DSSTS scheme's 2,4,6,8 and 10 transmit antenna scenarios all performed the same, viz. a 12.5dB gain is obtained over Alamouti's original 2 transmit antennas scheme at a BER of 10^{-4}.
- For a single user the DSSTS scheme's 2,4,6,8 and 10 transmit antenna scenarios performed 1dB worse than in a AWGN channel scenario at a BER of 10^{-4}.

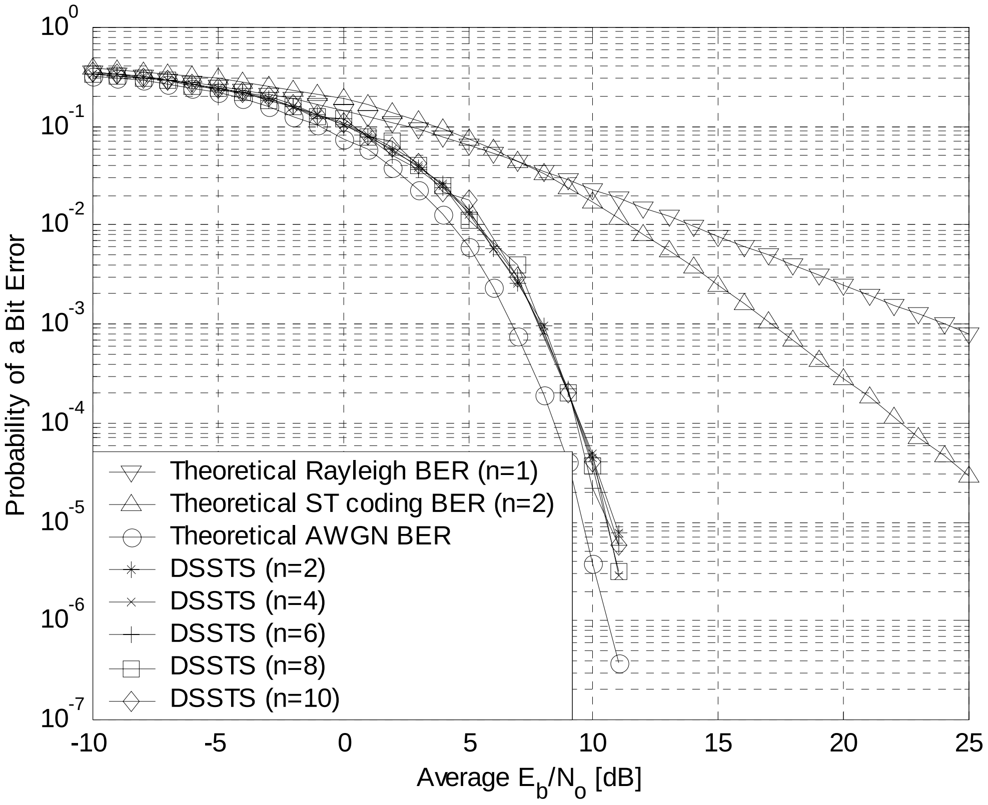

Figure 6.9. Single user performance evaluation for the DSSTS's 2 to 10 antennas in a Rician fading environment with K = 6dB and f_d = 100Hz.

In order to show the effect of the Doppler spread on the BER performance of the DSSTS scheme in a Rician fading environment (K = 6dB), BER performance graphs were generated for different Doppler frequencies. The number of transmit antennas was kept constant for each graph. These graphs are presented in *Figures 6.12, 6.13, 6.14, 6.15* and *6.16* and the following observations can be made:

- As opposed to some of the Rayleigh fading environment scenarios, no improved BER performance for a single user was obtained for higher Doppler frequencies in a Rician fading environment with a LOS to NLOS ratio of 6dB.
- This can mainly be attributed to the fact that the signal envelope is more constant with a Rician factor of 6dB, and no deep fades occurred for long periods, irrespective of the Doppler frequency.
- Note that the reference curve is the theoretical ST coding BER curve in Rayleigh fading

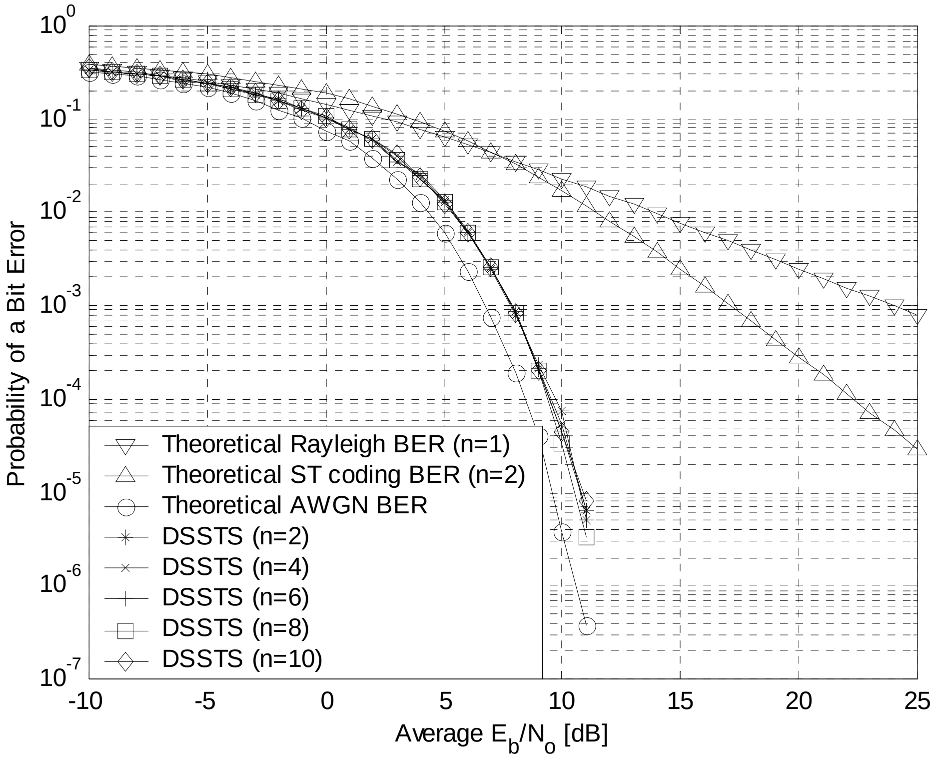

Figure 6.10. Single user performance evaluation for the DSSTS's 2 to 10 antennas in a Rician fading environment with K = 6dB and f_d = 66Hz.

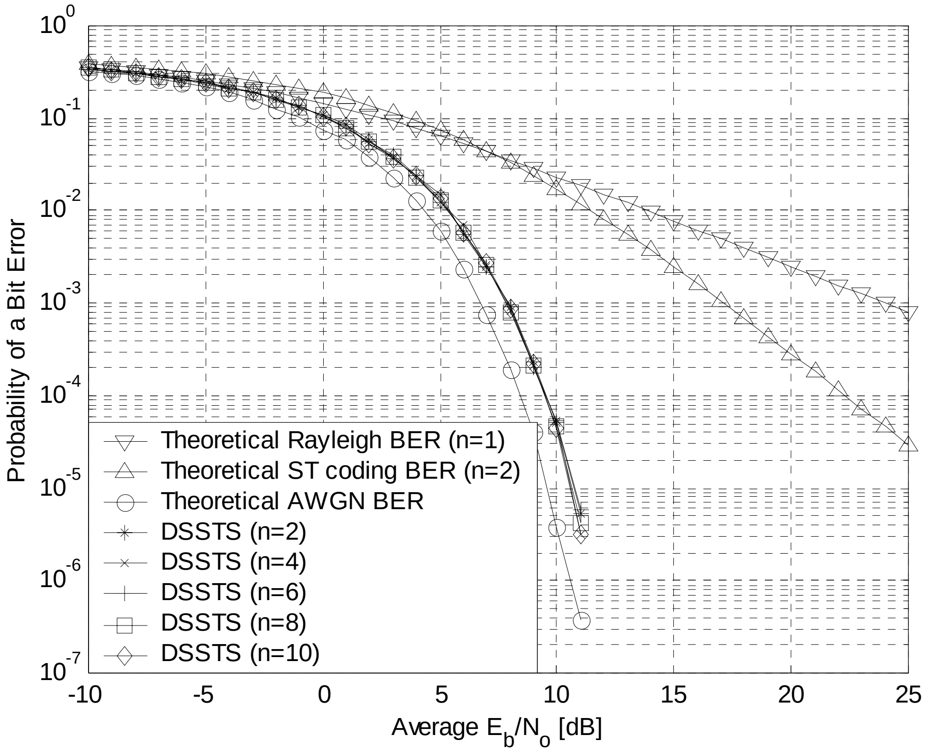

Figure 6.11. **Single user performance evaluation for the DSSTS's 2 to 10 antennas in a Rician fading environment with K = 6dB and f_d = 33Hz.**

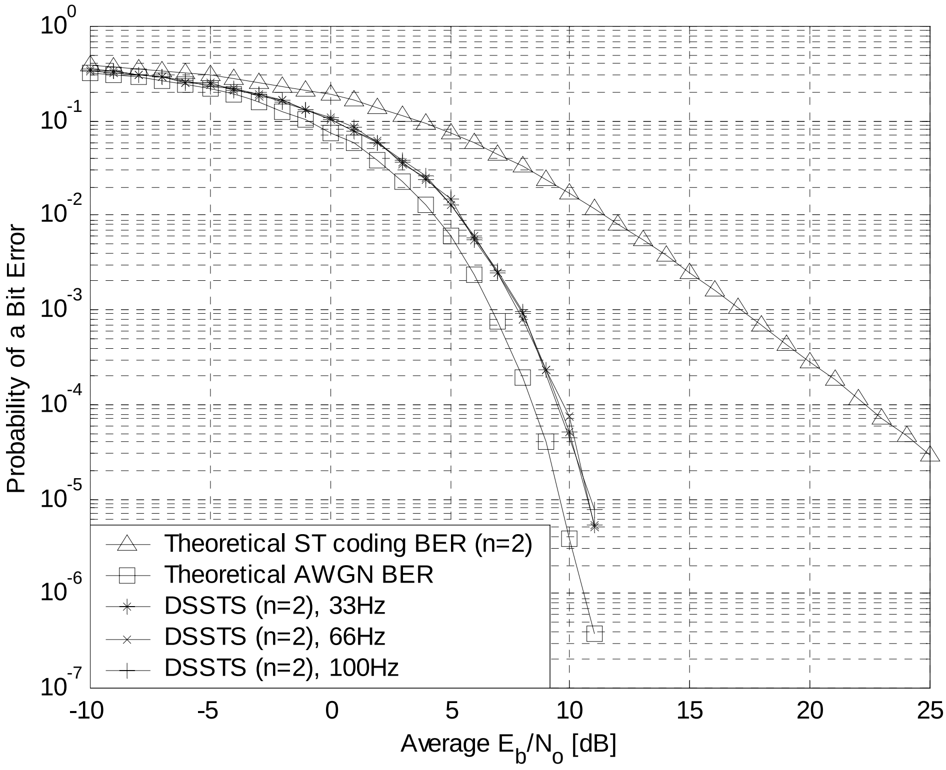

Figure 6.12. **Single user performance evaluation for the DSSTS's 2 antenna scenario in a Rician fading environment with K = 6dB at different values of f_d.**

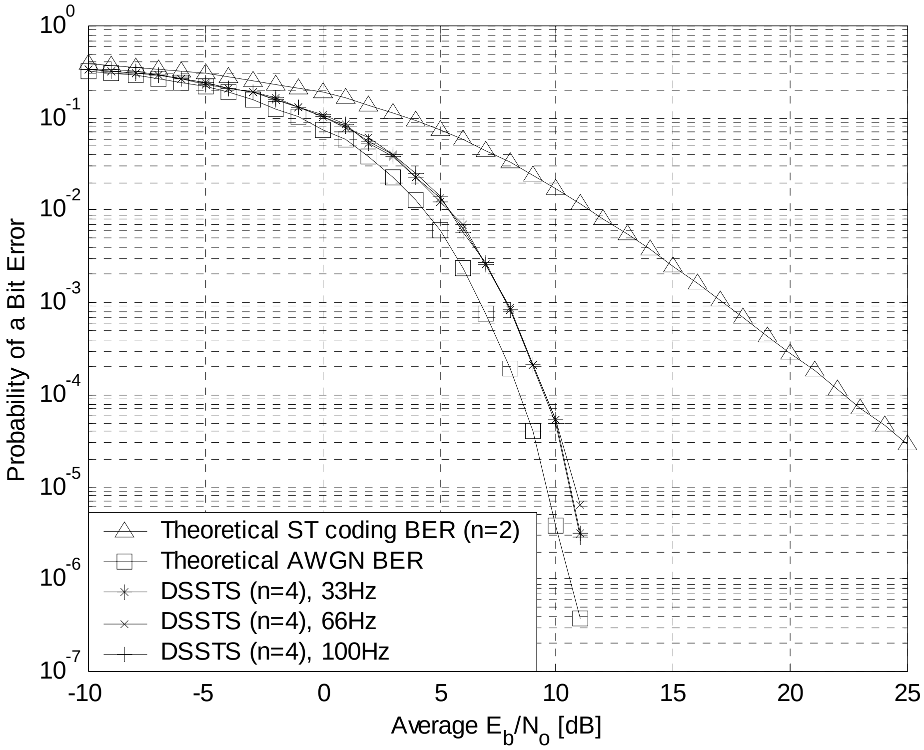

Figure 6.13. **Single user performance evaluation for the DSSTS's 4 antenna scenario in a Rician fading environment with K = 6dB and different values of f_d.**

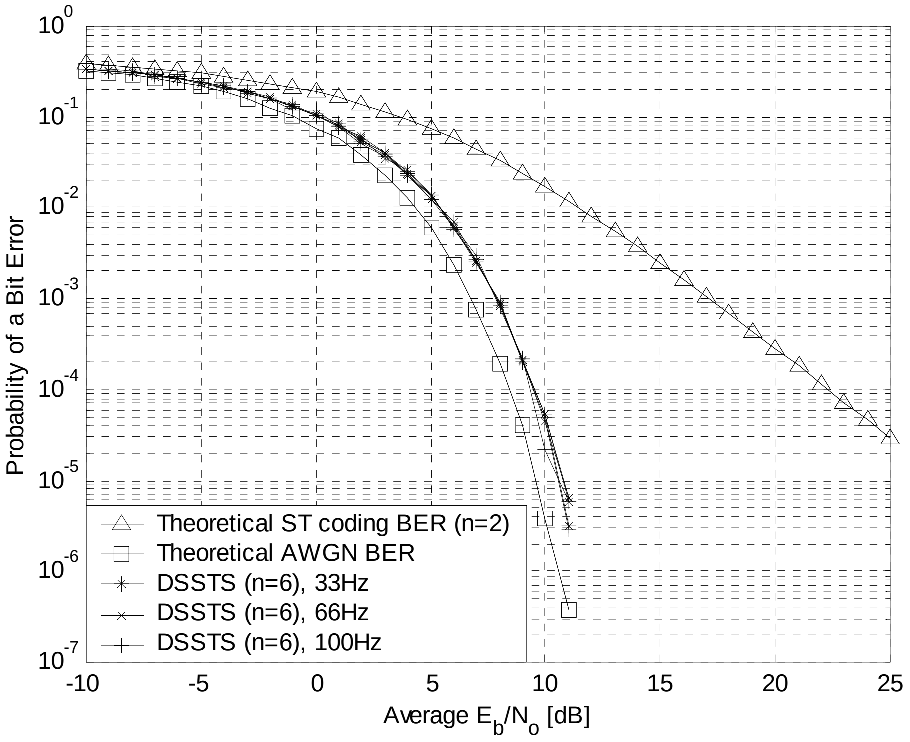

Figure 6.14. **Single user performance evaluation for the DSSTS's 6 antenna scenario in a Rician fading environment with K = 6dB and different values of f_d.**

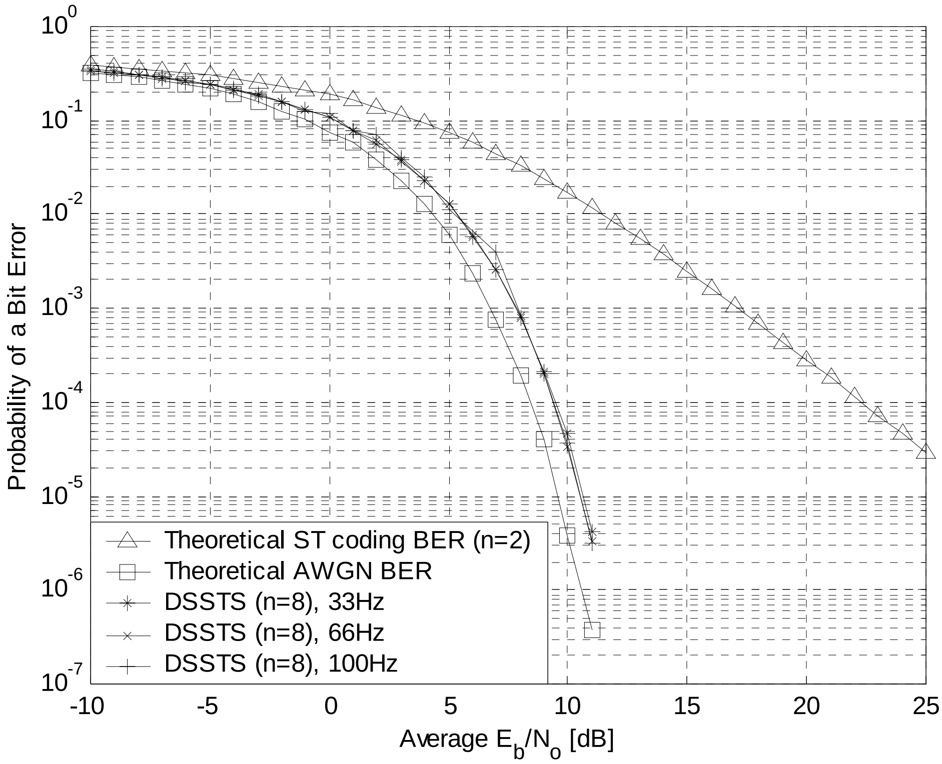

Figure 6.15. Single user performance evaluation for the DSSTS's 8 antenna scenario in a Rician fading environment with K = 6dB and different values of f_d.

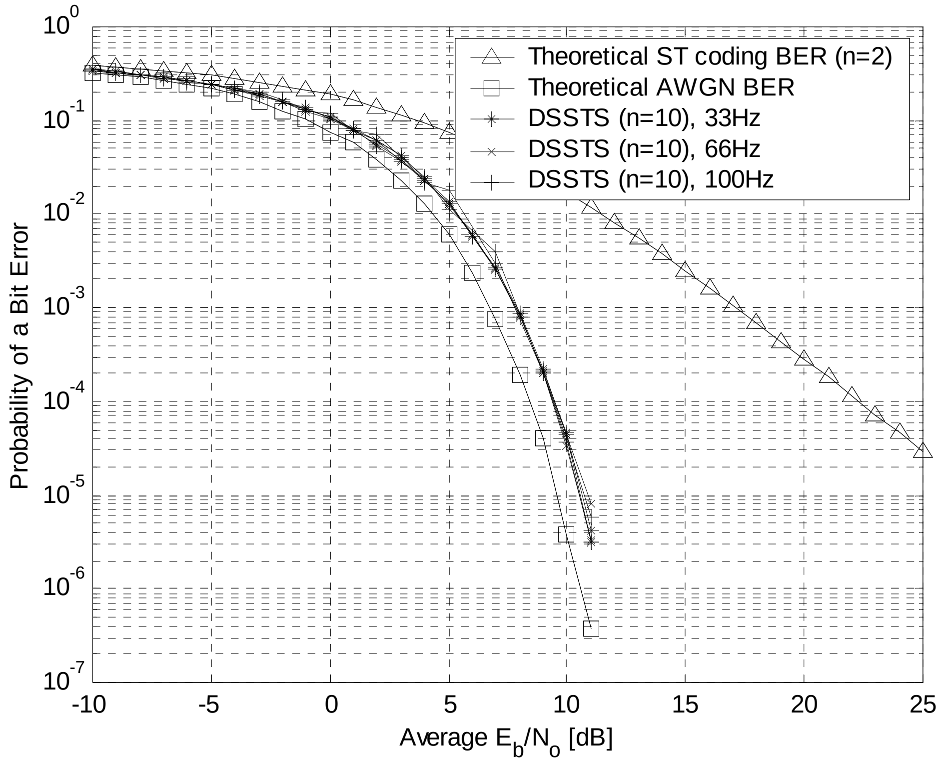

Figure 6.16. Single user performance evaluation for the DSSTS's 10 antenna scenario in a Rician fading environment with K = 6dB and different values of f_d.

6.1.3 Performance results of a Rayleigh versus Rician fading environment

In *Figures 6.17, 6.18, 6.19, 6.20* and *6.21* simulated BER performance curves are presented for 2, 4, 6, 8 and 10 transmit antennas, in a Rayleigh as well as Rician fading environment. Once again, the simulation platform presented in *Chapter 5, section 5.1.6* were used to simulate these effects. Also note that Alamouti's original 2 transmit antenna scheme is included as a reference benchmark. From *Figures 6.17* to *6.18*, it can be seen that an improved BER performance is obtained for a Rician fading environment over a Rayleigh fading environment. This is expected, as a Rician fading environment has an LOS visibility between the MS and BS whereas in a Rayleigh fading environment no direct LOS exists between the MS and BS (see *Chapter 4* and Appendix C).

For the DSSTS's scheme's 2 transmit antenna scenario presented in *Figure 6.17*, the following important observations can be made:

- In a Rician fading environment with f_d = 33Hz, the 2 transmit antenna scenario obtained a 5dB gain over a Rayleigh fading environment at a BER of 10^{-4}.
- However, this gain decreased to 4dB for Doppler frequencies of 66Hz and 100Hz. The decreased gain is due to the fact that a Rician fading environment has a constant BER performance for all Doppler frequencies opposed to Rayleigh fading environment where BER performance gains is obtained by increasing the Doppler frequency.

For the DSSTS scheme's 4 transmit antenna scenario, presented in *Figure 6.18*, the following important observations can be made:

- In a Rician fading environment with f_d = 33Hz, the 4 transmit antenna scenario obtained a 4dB gain over a Rayleigh fading environment at a BER of 10^{-4}.
- However, this gain decreased to 3.3dB for Doppler frequencies of 66Hz and 100Hz for the same reasons described in the 2 transmit antennas scenario.

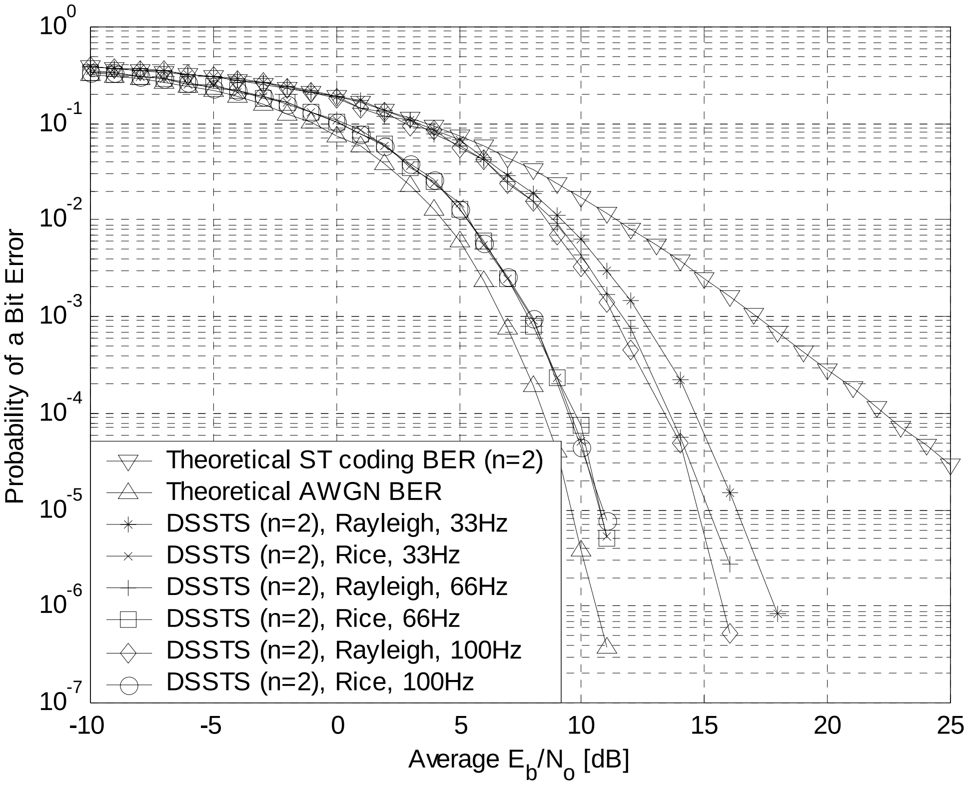

Figure 6.17. 1-user performance evaluation for the DSSTS's 2 antenna scenario in a Rayleigh vs. Rician (K=6dB) fading environment for different values of f_d.

For the DSSTS scheme's 6 and 8 transmit antenna scenario, presented in *Figures 6.19* and *6.20*, the following important observations can be made:

- Simulating the DSSTS scheme's 6 and 8 transmit antennas scenarios in a Rician fading environment with f_d = 33Hz, a gain of 3.5dB is obtained over a Rayleigh fading environment at a BER of 10^{-4}.
- However, this gain decreased to 3dB for Doppler frequencies of 66Hz and 100Hz for the same reasons described in the 2 transmit antennas scenario.

For the DSSTS scheme's 10 transmit antenna scenario, presented in *Figure 6.21*, the following important observations can be made:

- With a Rician fading environment the 10 transmit antenna scenario obtained a 3dB gain over a Rayleigh fading environment at a BER of 10^{-4}.
- However, this gain is similar for all three different Doppler frequencies. Once again, the same reasoning as described for the 2 transmit antennas scenario can be followed for this case as well.

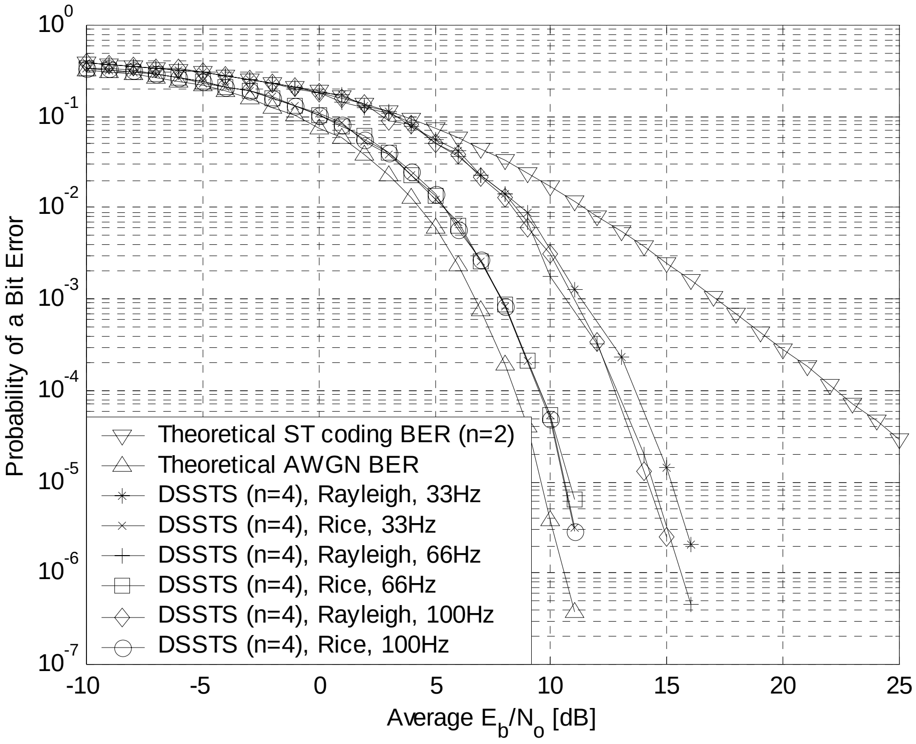

Figure 6.18. 1-user performance evaluation for the DSSTS's 4 antenna scenario in a Rayleigh vs. Rician (K=6dB) fading environment for different values of f_d.

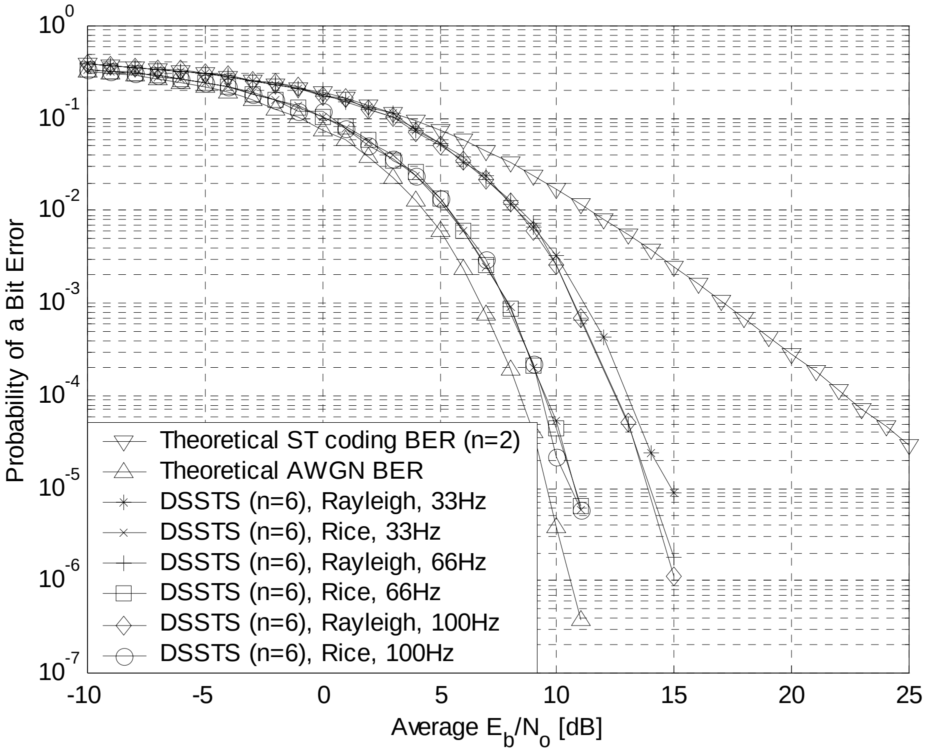

Figure 6.19. 1-user performance evaluation for the DSSTS's 6 antenna scenario in a Rayleigh vs. Rician (K=6dB) fading environment for different values of f_d.

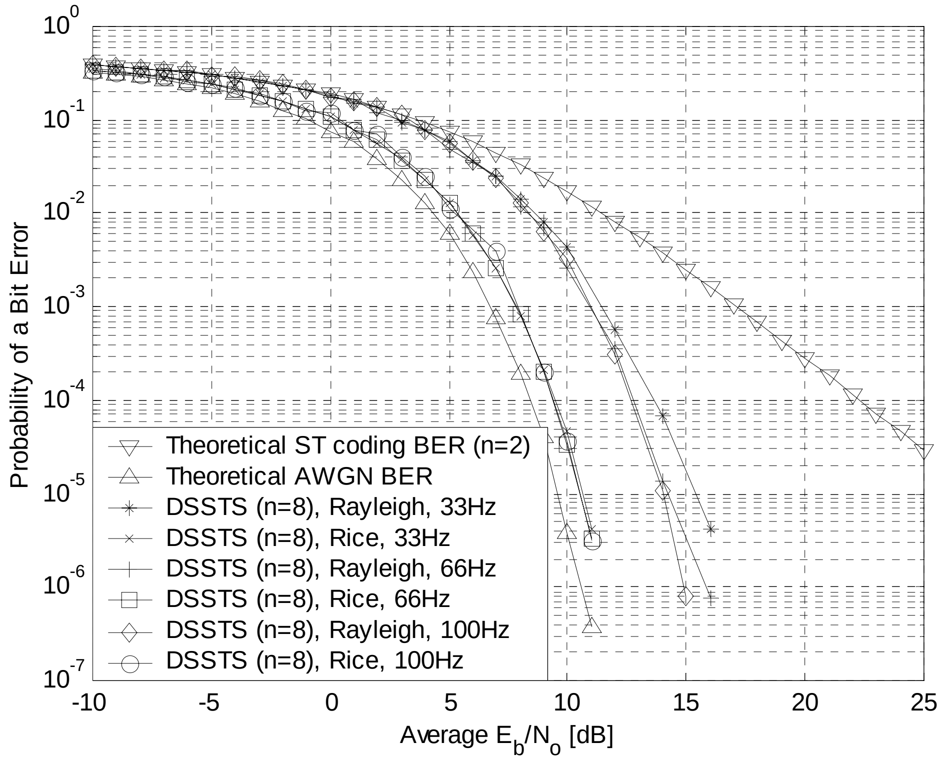

Figure 6.20. 1-user performance evaluation for the DSSTS's 8 antenna scenario in a Rayleigh vs. Rician (K=6dB) fading environment for different values of f_d.

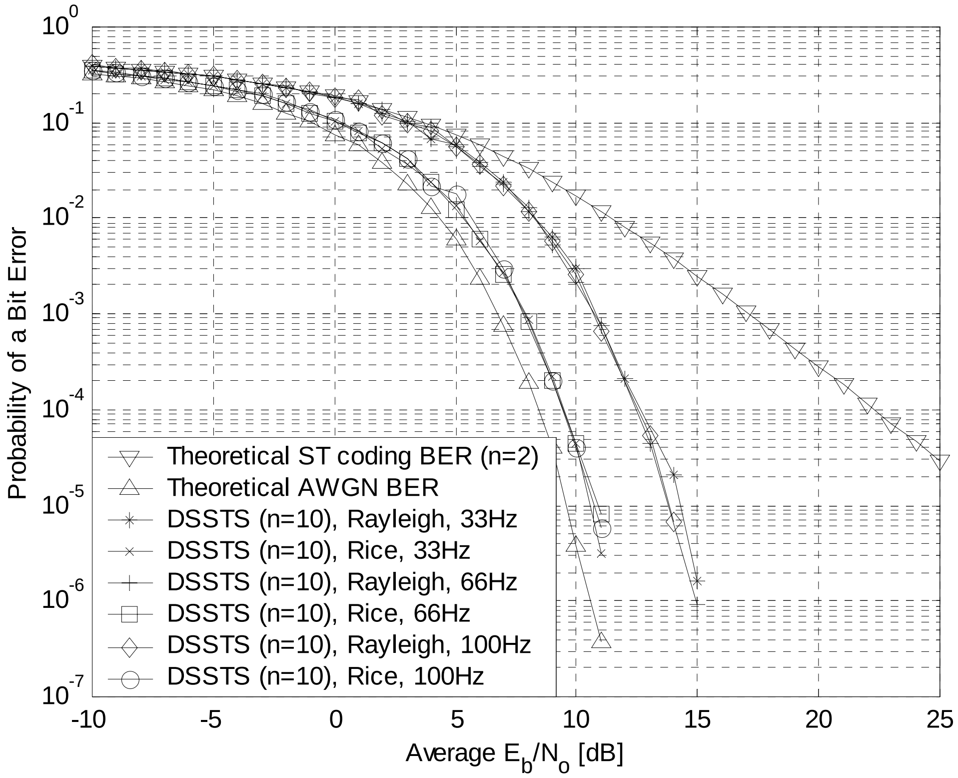

Figure 6.21. 1-user performance evaluation for the DSSTS's 10 antenna scenario in a Rayleigh vs. Rician (K=6dB) fading environment for different values of f_d.

6.2 DSSTS CAPACITY

A plot of the capacity CCDFs of (1x1) and (2x2) communication systems is presented in *Figure 6.22*. Important observations that can be made from *Figure 6.22* are as follows:

- At 10% channel capacity outage, the capacity of a (2x2) MIMO system has 3.3 times the capacity of a traditional (1x1) SISO system. In fact, at small SNR (i.e. 0dB to 3dB), the (2x2) MIMO system has a capacity of 6 times larger than a traditional (1x1) system.
- With a 3dB increase in SNR for a SISO system, i.e. doubling in power, the 10% capacity outage increased by 1.7 times the current channel capacity.
- With a 3dB increase in SNR for a MIMO system, the 10% capacity outage increased by 1.5 times the current channel capacity.

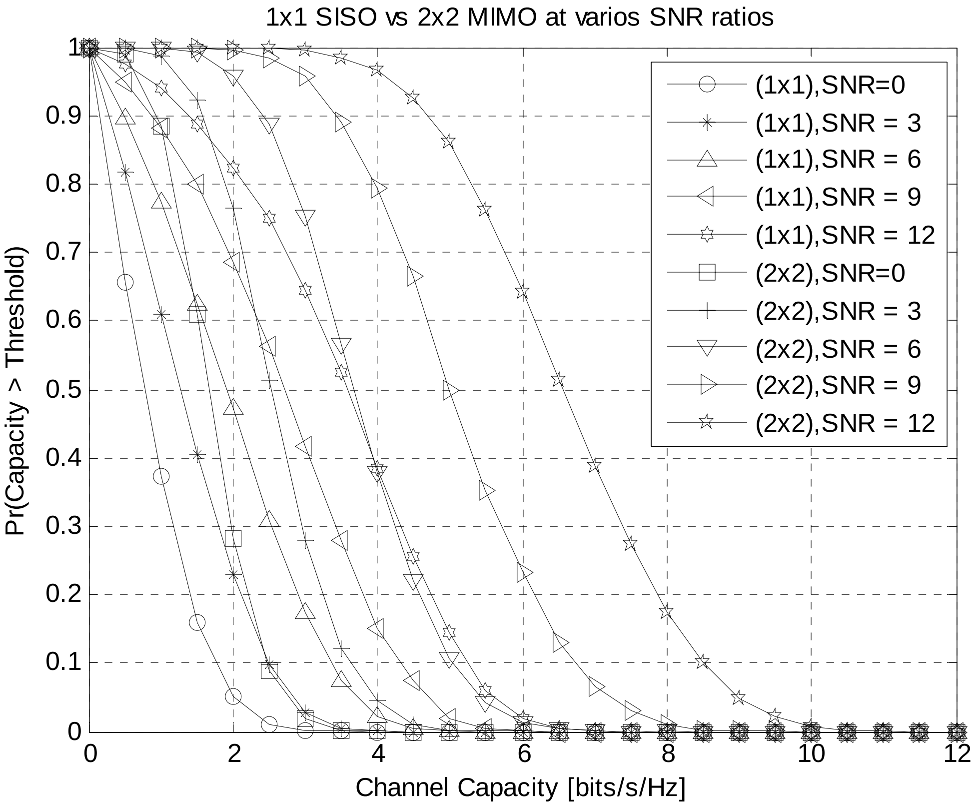

Figure 6.22. Capacity CCDFs of a (n = 1, m = 1) and (n = 2, m = 2) system.

Capacity plots for the DSSTS schemes at a SNR = 21dB, with 2, 4, 6 and 8 transmit antennas are plotted in *Figure 6.23* (see *Chapter 5, Section 5.1.5, Equation (5.64)*). From *Figure 6.23*, the following important observations can be made:

- The capacity increases as the number of transmit antennas increases.
- The (2x1) DSSTS scheme obtains a capacity increase of 1.3 bits/s/Hz over the (1x1) SISO system at a capacity outage of 10%.
- The (4x1) DSSTS obtains a further capacity increase of 0.6 bits/s/Hz over the (2x1) DSSTS system at a capacity outage of 10%.
- The (6x1) DSSTS only obtains a 0.25 bits/s/Hz capacity increase over the (4x1) DSSTS system at a capacity outage of 10%.
- The (8x1) DSSTS only obtains a 0.1 bits/s/Hz capacity increase over the (6x1) DSSTS system at a capacity outage of 10%.
- As the DSSTS number of transmit antennas tends to infinity, the capacity increase tend to zero.

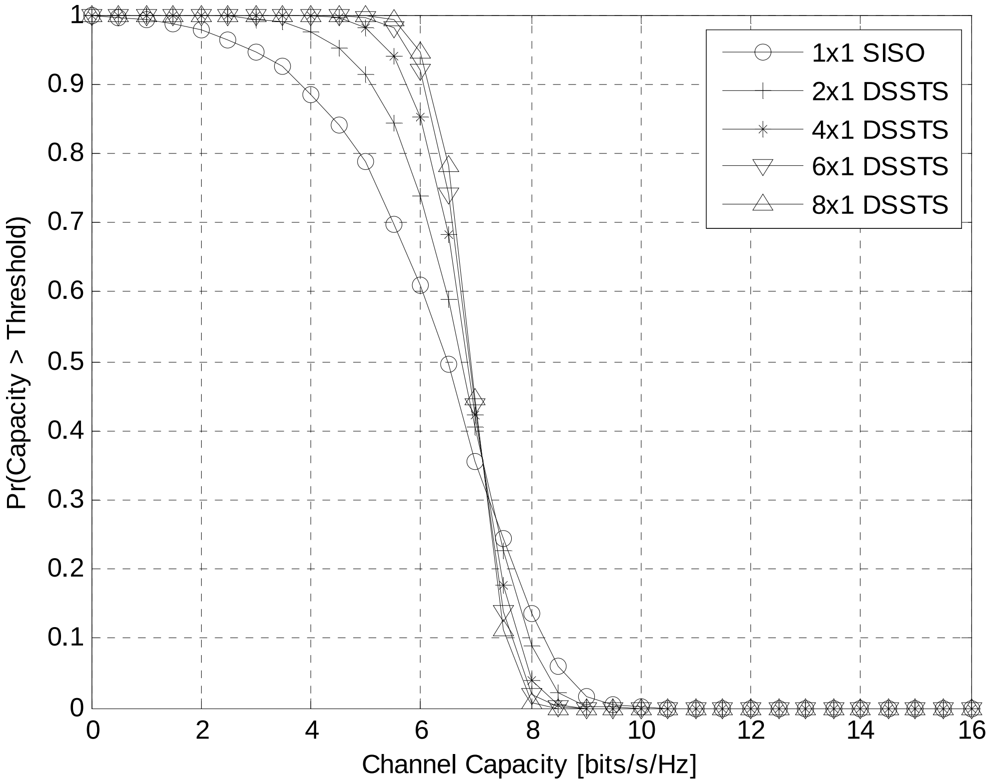

Figure 6.23. Theoretical capacity CCDFs of the DSSTS scheme with 2, 4, and 8 transmit antennas at a SNR = 21dB.

Capacity plots of other transmit diversity schemes, i.e. the Zero Forcing (ZF) [18] and a (4x1) transmit diversity scheme proposed by [18], are presented in *Figure 6.24*. These are included to show the relative performance of the DSSTS schemes. From *Figure 6.24*, the following important observations can be made:

- The (4x1) DSSTS outperforms the other transmit diversity schemes.
- The (4x1) DSSTS obtains a capacity advantage of 0.25 bits/s/Hz over the (4x1) scheme presented in [18] at a capacity outage of 10%.
- The (4x1) DSSTS obtains a capacity advantage of 0.6 bits/s/Hz over the (4x1) ZF system at a capacity outage of 10%.
- Note that much greater capacity is obtained with the (2x2) MIMO system.

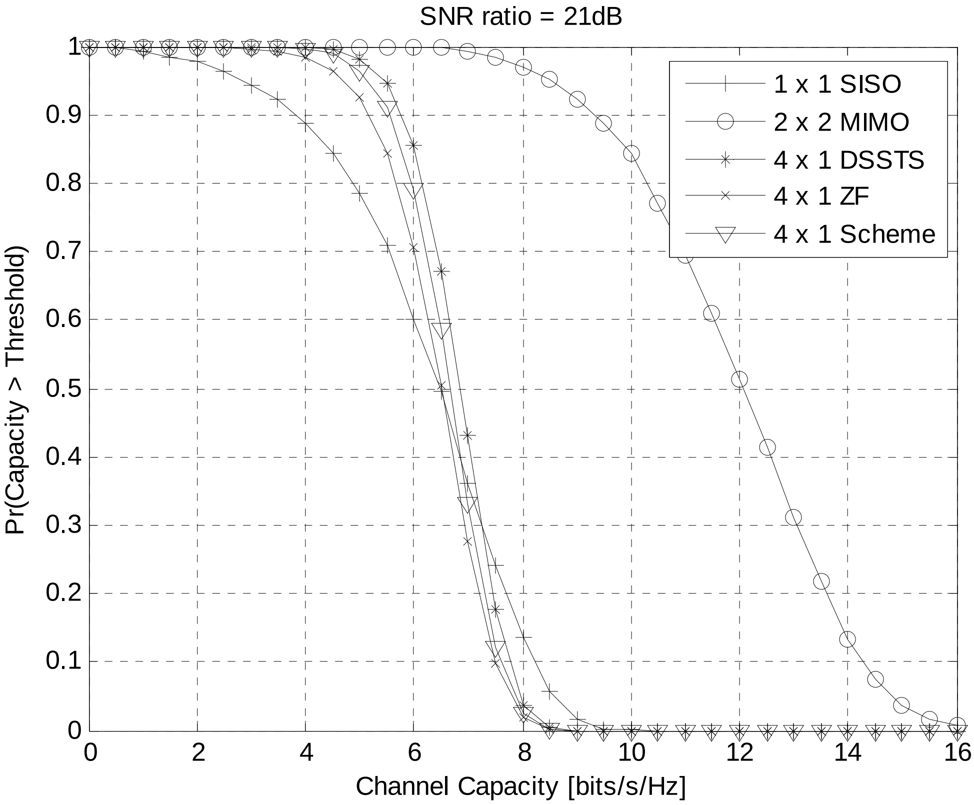

Figure 6.24. Theoretical capacity CCDFs of a (4x1) scheme and a ZF method [18] compared to the DSSTS scheme.

CHAPTER SEVEN

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

This dissertation was structured as follows. Firstly, background information on ST coding and spread spectrum modulation techniques were presented. Secondly, a flat fading performance evaluation platform for the DSSTS scheme was presented. This baseband simulation model is capable of replicating the operation of a realistic flat fading channel, without the requirement of carriers and high sampling frequencies. This flat fading channel was also used as a platform for the multipath fading channel described and presented in *Chapter 4*. Thirdly, the DSSTS scheme's encoding and decoding structures were presented, which are capable of improving on communication system's throughput and channel capacity. A theoretical capacity equation was also derived for the DSSTS. Fourthly, the unrealistic ST coding assumption of the channel being quasi-static for low throughput rates with high Doppler frequencies were addressed with the SSTD scheme and a versatile complex multi-user multipath fading performance evaluation platform for the proposed SSTD scheme was described. Lastly, simulation results were presented and conclusive remarks will be made on these during the remainder of this chapter.

From the discussions on the results presented in *Chapter 6*, a number of conclusions can be made. The conclusions discussed during the remainder of this chapter include:

- The performance of the DSSTS scheme in a Rayleigh fading environment,

- the performance of the DSSTS scheme in a Rician fading environment,
- a comparison of the DSSTS scheme's performance in a Rayleigh versus Rician fading channel,
- the capacity increase obtained by using DSSTS, and lastly
- general conclusions and proposals for future work on the DSSTS scheme.

7.1 RAYLEIGH FADING

It is known that in digital communication systems the Doppler frequency does not have an effect on the BER of uncoded modulation systems. However, if the digital communication system employs coding, the BER is effected by the Doppler frequency. DSSTS, although not conventional coding, can be viewed as a scheme with "coding through diversity" because a symbol is send through different channels to the receiver. These multiple copies of a symbol are received at the receiver and combined into one symbol again. Hence, if the DSSTS is a "channel code", it can be classified under communication systems employing coding and will depend on the Doppler frequency as seen from the simulation results. However, this discussion of Doppler frequency vs. the DSSTS scheme's BER needs to be verified by further simulations and will be a topic for future research.

By keeping the above discussion in mind, the number of transmit antennas in a Rayleigh fading environment has an effect on the performance of the DSSTS scheme at low and high mobile velocities: At low velocities, i.e. a low Doppler frequency, the DSSTS's 10 transmit antenna scenario had a 9.5dB gain over Alamouti's original 2 transmit antenna scheme, and a 2dB gain over the DSSTS scheme's 2 transmit antenna scenario at a BER of 10^{-4}. At high velocities, i.e. a high Doppler frequency, the DSSTS's 10 transmit antenna scenario had an 8.5dB gain over Alamouti's original 2 transmit antenna scheme and a 1dB gain over the DSSTS scheme's 2 transmit antenna scenario at a BER of 10^{-4}. Thus, for high Doppler frequencies, the gains realized by increasing the number of transmit antennas from 2 to 10 may not be cost effective. Although better performance is obtained by increasing the number of transmit antennas at low Doppler frequencies, it is also not cost effective, since only a 2dB gain is realized. It should also be noted that the highest gain, i.e. a gain of 7.5dB at a BER of 10^{-4}, was obtained over the traditional 2 transmit antenna scenario presented by Alamouti and spreading the 2 transmit antennas with a Walsh sequence. The reason for the DSSTS scheme's poor performance is that despreading is done following the RF stage and leaves no room for phase correction, equalisation or RAKE reception (see *Chapter 5, Figure 5.1*). Note that phase correction is only done during the ST decoding fase. As a result of no phase error corrections made at the receiver during the despreading fase, non-perfect cross-correlation is experienced and results in antenna self-noise created from the spreading sequences used on different transmit antennas. The problem with the antenna self-noise was addressed in *Chapter 5, Section 5.1.4*. Another way of viewing the lack of performance of the DSSTS scheme is that the diversity gain obtained by adding another antenna, is not sufficient to overcome the antenna self-noise caused by adding another code associated with that antenna. From *Figure 7.1* it can be seen that the BER performance increases as the number of transmit

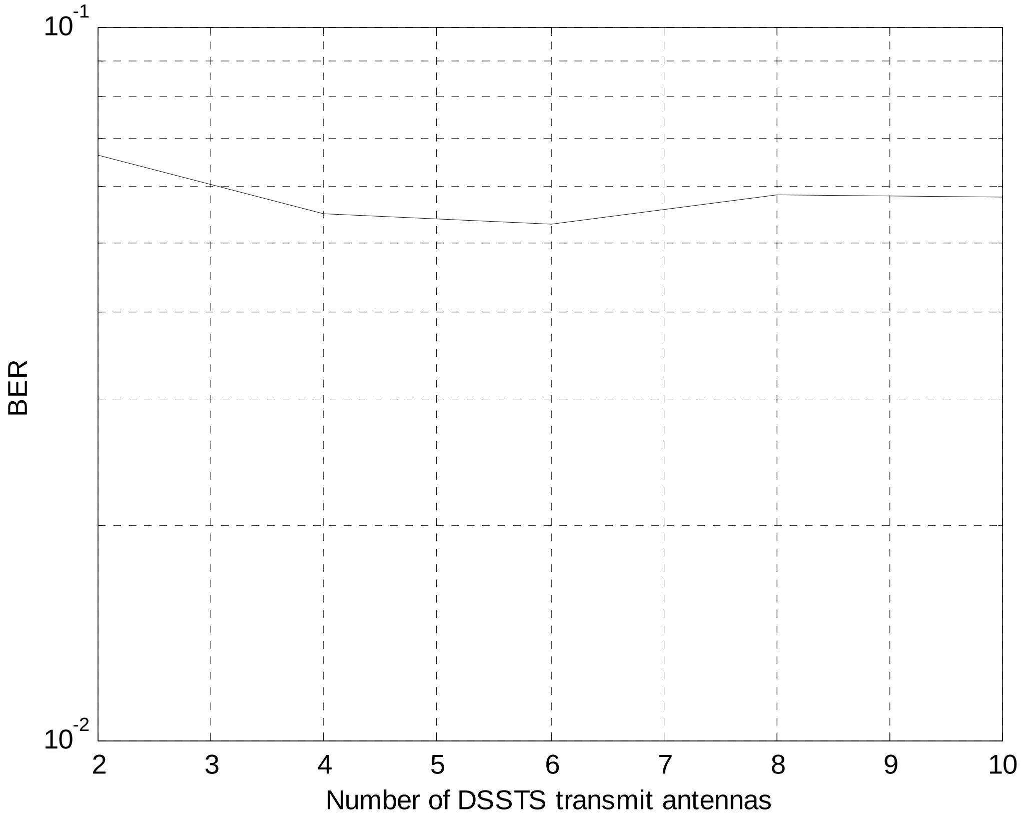

Figure 7.1. A single user DSSTS scheme's BER performance in a Rayleigh fading channel for 2 to 10 transmit antennas at E_b/N_0 = 5dB, f_d = 33Hz.

antennas increase up to 6 transmit antennas. Thereafter, the BER decrease as antenna self-noise exceeds the diversity gains obtained. Note that this statement is only true for this particular dissertation's DSSTS scheme and can possibly be corrected by further research, as discussed in more detail in *Section 7.4.*

7.2 RICIAN FADING

In a Rician fading environment the number of transmit antennas does not have a marked effect on the performance of the DSSTS scheme at low and high mobile velocities. Thus, the effect of Doppler spread, i.e. the speed at which the mobile moves, in contrast to the Rayleigh fading scenario, has no effect on the DSSTS schemes BER at a Rician Factor of 6dB. Similar to the Rayleigh fading channel, the case of spreading the 2 transmit antennas by a Walsh sequence had the highest gain. A gain of 12.5dB at a BER of 10^{-4} was *Chapter 6*, it is evident that there exists an optimal trade-off between diversity and antenna

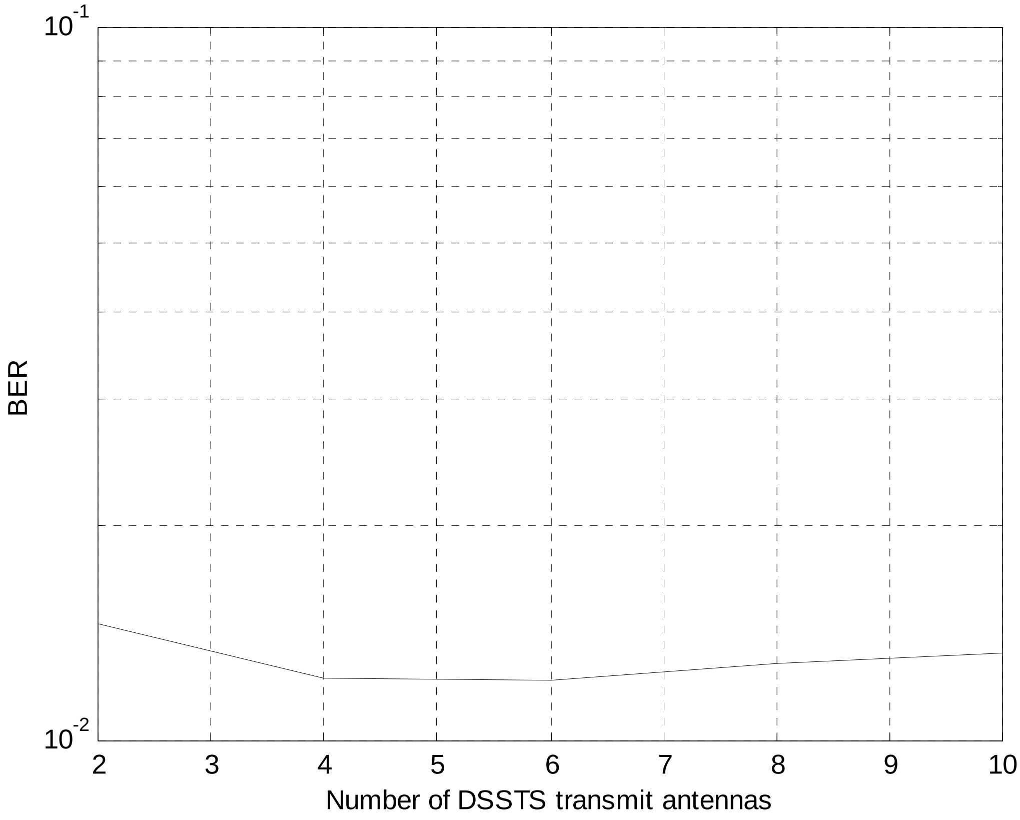

Figure 7.2. A single user DSSTS scheme's BER performance in a Rician fading channel for 2 to 10 transmit antennas at E_b/N_0 = 5dB, f_d = 33Hz.

obtained over the traditional 2 transmit antenna scenario presented by Alamouti. The performance of the DSSTS scheme's 2 transmit antenna scenario performed within 1dB of the performance of an uncoded system in an AWGN channel. From the results obtained inself-noise. In the case of the DSSTS scheme performing in a Rician fading channel, the 2 transmit antenna scenario obtains most of the diversity gain. By adding further transmit antennas, no significant transmit diversity gains is obtained. As was the case in the Rayleigh fading channel, the diversity gain obtained by adding another antenna, is not enough to overcome the antenna self-noise caused by adding the additional antenna. From *Figure 7.2* it can be seen that the BER performance increases as the number of transmit antennas increases up to 4 transmit antennas and once again decreases as antenna self-noise becomes greater than diversity gains.

7.3 DSSTS CAPACITY

From the capacity plots presented in *Chapter 6, Section 6.2*, it is evident that the capacity of a traditional one transmit, one receive antenna system can be increased by adding multiple transmit and receive antennas. In fact, a (2x2) MIMO system has a capacity three times greater than a traditional (1x1) SISO system at a capacity outage of 10%. However, with reference to *Figure 6.22*, every doubling in transmit power, the traditional SISO system capacity increase is slightly more than the capacity increase experienced in a MIMO system.

In this dissertation, only increasing the number of transmit antennas to more than four has been investigated. By increasing the number of transmit antennas, the capacity of the DSSTS system increases. However, as the number of transmit antennas increases, less capacity gain is obtained. Thus, as the number of transmit antennas tend to infinity, the capacity increase tends to zero. From an economical point of view, it seems that the amount of capacity gain obtained by adding an extra transmit antenna beyond six transmit antennas does not warrant the effort nor complexity nor cost. Note that this only applies to transmit diversity, as a (4x4) MIMO system has a huge capacity advantage over a (2x2) MIMO system.

It was furthermore shown that the DSSTS scheme obtained the same open-loop capacity gain as the theoretical open-loop capacity gain for a transmit diversity scheme. Note that this only applies to the Rayleigh fading case, as it is known that the channel capacity decreases [71] with a LOS component present in the channel, i.e. with a Rician fading channel.

7.4 RAYLEIGH VERSUS RICIAN FADING

From the discussions and results presented in *Chapter 6*, the following conclusion can be made on the effect different flat fading channel conditions has on the DSSTS scheme's performance.

Under Rician fading conditions the DSSTS scheme outperforms the DSSTS scheme in Rayleigh fading conditions, as would be expected. However, as the number of transmit antennas increases, the performance advantage of the Rician fading channel over the Rayleigh fading channel decreases. The reason for the performance advantage of the Rician fading channel over a Rayleigh fading channel is mainly due to the presence of a LOS component between the BS and MS, implying that the received signal's envelope is more constant without deep fades.

With less transmit antennas at the BS, i.e. 2, 4 and 6 transmit antennas, poor BER performances are obtained at low mobile speeds, i.e. low Doppler frequencies. Relative to the low mobile speeds, an improved BER performance is obtained when the mobile's speed increases, i.e. with high Doppler frequencies. The poor BER performance with low mobile speeds is mainly due to the received complex faded signals' tendency to be in deep fades for longer periods of time than at the high mobile speed scenarios, thus causing burst errors. However, as stated above, mobile velocity doesn't have a significant effect on the performance of the DSSTS scheme in a Rician fading environment.

With a high number of transmit antennas at the BS, e.g. 10 transmit antennas, the BER performance in Rayleigh as well as Rician fading channel conditions remains practically identical, with a large spreading derived diversity gain compared to the Alamouiti 2 transmit antenna case, regardless of the speed of the mobile. The lack of significant BER performance gain can be attributed to a neutralisation of additional diversity gain by a corresponding increase in antenna self-noise caused with increasing number of transmit antennas, as stated in the sections above.

7.5 GENERAL CONCLUSIONS AND FUTURE WORK

By using the DSSTS scheme presented in this dissertation, the theoretical diversity gains obtainable are not satisfactorily achieved. As outlined above, this was mainly due to antenna self-noise caused amongst the spreading codes allocated to different transmit antennas. Future research can be done to utilize antenna self-noise cancellation techniques on the DSSTS scheme in order to obtain more diversity gains. Another possibility is to use different carrier frequencies for each transmit antenna, thus eliminating the antenna self-noise problem by employing a Frequency Division Multiple Access (FDMA) scheme. This would however lead to a spectral deficiency problem characteristic of FDMA methods.

One possible scenario is to remove the Alamouti code and use a spreading code at each antenna, with the spreaded transmitted symbols rotated in a fashion similar to the DSSTS scheme over all of the transmit antennas. This scheme has the advantage that each substream can be phase corrected at the receiver side, but has the disadvantage that 50% more spreading codes are required compared to the DSSTS scheme. One main objective that was achieved employing the DSSTS scheme presented in this dissertation, was to save on the number of spreading codes, when compared to STS [65]. Besides a possible FDMA system, a TDMA scheme can also be considered as an alternative to combat antenna self-noise induced by the use of multiple spreading codes in the DSSTS scheme.

Another possibility would be to swap the spreading and the Alamouti code. Thus, place the Alamouti code at the channel side in order to resolve the phase rotation introduced by the complex fading channel and then do the despreading. A problem with this scenario is that the number of transmit antennas can not be extended to more than 4 transmit antennas to obtain both full rate and full diversity, because of the lack of orthogonal transmit matrices for more than 4 transmit antennas, as presented in *Chapter 2, Sections 2.3* and *2.6*.

Instead of using the Alamouti ST block code, a differential detection scheme that is not dependant on CSI, can be used. Thus, CSI can now be used in the despreading of the received signal in order to improve cross-correlation between spreading sequences. However, it is known that a penalty of 2dB [49] is paid for using a differential detection scheme.

In this particular dissertation only a QPSK symbol constellation was used. Further research can also be done by using different symbol constellations in the DSSTS scheme, as this has a direct impact on the channel capacity of the system.

In this dissertation only cross-correlation amongst spreading codes was considered crucial, because the DSSTS scheme was only simulated in flat fading channel conditions. However, in more realistic channel conditions, a multipath channel should be considered. If this were the case, auto-correlation, as well as cross-correlation would affect the performance of the DSSTS scheme. In the mathematical formulation of the DSSTS scheme, it was assumed that the cross-correlation between different Walsh spreading sequences is zero. However, when it is non-zero, the symbols transmitted on the other antennas act as antenna self-noise. Thus, in the case of 8 transmit antennas, 4 times as much antenna self-noise will be generated compared to the 2 transmit antenna scenario, thereby degrading the diversity gain that was achieved (see *Chapter 5, Section 5.1.4*). In this dissertation it was assumed that the channel is quasi-static over the frame length of the code words. When this assumption is relaxed so that the channel is quasi-static over 2 time-periods in a frame-length codeword, a 3dB penalty is paid, because half of the noise doesn’t cancel out, as seen in *Chapter 5, Section 5.1.4*. Thus, future research can also be directed to finding spreading sequences that exhibit perfect cross – and auto-correlation that can be used with the DSSTS scheme in order to minimise the antenna self-noise of the scheme.