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Relay Signal Combination to Improve Long Range Communication with Multiple Relays

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Executive Summary

This report documents the results of research into a long-range communications technique involving a single transmitter, multiple redundant relays, and baseband signal-combining at the receiver. In this approach, the transmitter broadcasts to a cluster of inexpensive, airborne relays which re-broadcast the same signal on different frequencies. Distant receivers combine multiple weak signals and time-align them to improve the overall channel bit error rate. There are several advantages of using this multiple relay approach. They include:

- Eliminates the single point of failure of traditional approach (satellite, aircraft, large drones, etc.)
- Allows for both graceful degradation and enhancement of communications as relays are either lost or added to the area.
- Do not have to rely on a single relay being in the optimal location. (Relays may be difficult to place accurately or have specific airspace they are allowed to occupy.)
- Individual relays can reduce transmit levels if multiple weak links can be combined into an adequate composite signal. With lower transmit levels, battery life and range life can be extended.
- Reducing transmit levels also allows for lower probability of detection.

The benefits to an approach relying on multiple, redundant UAV relays can only be realized if the limitation of their inherently low signal levels can be overcome. This report shows the improvements obtained by combining these baseband signals at the receiver.

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Relay Signal Combination to Improve Long Range Communication with Multiple Relays

1. Introduction

1.1 Motivation

One important goal of Department of Defense (DoD) communications is to extend line of sight (LOS) communications reliably and inexpensively. Because of the cost, vulnerability, and limited bandwidth of satellites, the DoD cannot rely solely on satellites for beyond line of sight (BLOS) communications. In addition, the DoD also cannot rely predominantly on secondary methods such as piloted aircraft or expensive drones for BLOS communications.

In addition to standardizing interoperability specifications for tactical communication [1,2,3,4], the U.S. Naval Research Laboratory (NRL) has done significant work recently on implementing low cost communications electronics on relay balloons which could be discarded after one time use [5,6,7,8,9]. Recently with the development of small scale inexpensive *recoverable* unmanned aerial vehicles (UAVs), much of that early low cost balloon relay work can be transitioned to these small scale UAVs, assuming suitable antennas can be developed for the specific UAVs.

Applications of a Reliable Multiple Relay Communications Link

While achieving high bandwidth networked communications at the tactical edge can be advantageous, to achieve this presents several issues involving reliability, power consumption, network configuration, and link resource availability that must be supported. Many of these issues can be supported by having robust low bandwidth communications links that do not have single points of failure. This report documents the underlying techniques to build a reliable uncoordinated communication link for:

- **Robust communications:** A highly reliable link that is quickly available for critical communications when other high bandwidth links are not available.
- **Network control/configuration channel:** A robust network control channel to bring the high bandwidth network up initially, or after a network failure, that *does not depend on the network itself*.
- **Relaying low power transmissions:** A robust link is able to support users with reduced battery capacity and/or a limited ability to resupply power to their radio gear.

Advantages with respect to LPI/LPD of using multiple relays

The benefits to an approach relying on multiple, redundant relays also include the ability to operate these relays at very low transmission power levels. While low transmission levels have the inherent advantage of extending battery life, operating at low transmission levels also allows

relays to be used in low probability of intercept (LPI) / low probability of detection (LPD) applications.

1.2 Organization

This report is organized as follows:

Section 2 – Background: The background section will describe the necessary functions of the relays and receivers.

Section 3 – Design and Implementation/Technical Approach: This section describes the radio frequency (RF) relay communications model, receiver synchronization of multiple relay signals, fading channel environments, and the signal combination techniques used at receiver. Next is a description of all the designed test parameters of a simulation of the complete system.

Section 4 – Performance Analysis and Comparison: This section introduces the results of the simulation tests described in Section 3, followed by an evaluation of these results. For the sake of continuity, the extensive results section is presented in the appendix.

Section 5 – Conclusion and Future Research: This section gives a conclusion to this work and then outlines some possible next steps for research into improving results.

Appendix Results: Graphs detailing the results from 40 sets of test conditions are presented here.

2. Background

2.1 Relay Functions

The primary goal of this work is to focus the complexity of the system onto the receiver, not on the relays. The relays are designed to be simple and low cost. It is intended that each relay not rely on networking protocols or synchronization with other relays. The relays should only require minimal decoding or repackaging of the signals being relayed. Their only tasks are to receive communications, authenticate the user, and then retransmit on a different frequency, selected to be different from all the other relays before deployment. The relay does not decrypt, re-encode parameters, or resend with a different modulation.

2.2 Receiver Functions

The approach to combine relayed signals at the receiver will be within the digital baseband signal (bitstream) itself. In other words, the focus of this research will be on combining the demodulated digital baseband bitstreams together, not the analog RF waveforms themselves. By combining the relayed signals together after they are demodulated into the baseband bitstreams, this approach could lead to a more hardware agnostic solution where it does not matter which type of receiver demodulated each relayed signal.

The receivers' main tasks are to 1) receive these incoherent RF signals transmitted from multiple, uncoordinated relays, 2) decode the multiple relay signals into individual baseband bitstreams, 3) synchronize the bitstream signals in time without depending on GPS or network synchronization, and 4) combine the received bitstream signals into an improved signal for enhanced reception at the receiving platform. The relays would be resending (on different frequencies) the same information from a single source transmitter.

Relay signals may be degraded by fading channels (i.e. good channel performance goes in and out) especially because of low transmission power, transmitter and receiver antenna orientation/polarization, and non-ideal locations of relays. The receiver will use forward error control (FEC) to constantly monitor the performance of the degraded fading channel performance. The receiver will combine the relay signals with the signals weighted by how "good" each individual channel is performing at any given instance.

These receiver functions will be described much more completely in the following Technical Approach section of the report.

3. Design and Implementation/Technical Approach

As introduced above, combining incoherent signals transmitted from multiple, uncoordinated relays for enhanced reception at a single receiving platform is the primary goal of this project. The focus of the research will be on combining the individual baseband bitstream relay signals into one improved baseband bitstream signal. The technical approach presented below involves using three to five relays.

The Technical Approach will be presented in the following sections:

3.1 RF Relay Communications Model

3.2 Receiver Synchronization of Multiple Relay Signals

3.3 Fading channel environments

3.4 Signal combination techniques at receiver

3.5 Simulation of relay model, synchronization methods, communication methods, and signal combination techniques

3.1 RF Relay Communications Model

The model of the communication path between the Transmitter (TX), Relay, and Receiver (RX) setup with multiple relays is shown in Figure 1 below.

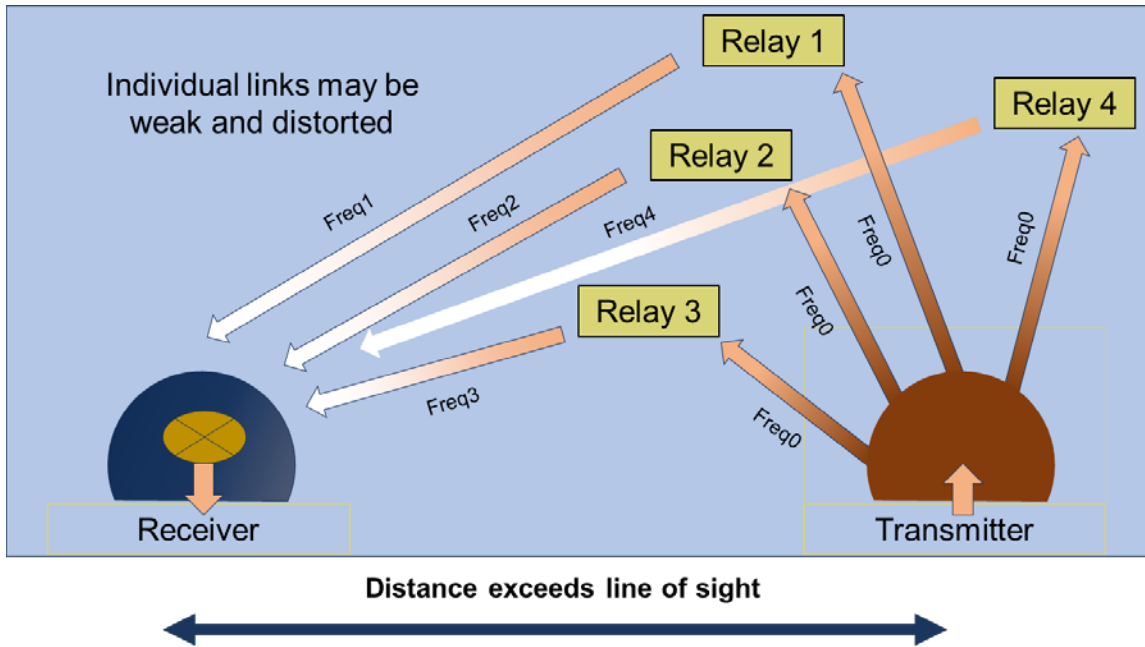


Figure 1 – Relay Communications Model: The model shows that one transmitter sends a common bitstream to multiple relays on a single frequency (Freq0). The multiple relays then retransmit it to the destination on different frequencies (Freq1 – Freq4). The receiver then demodulates these signals, aligns them, and combines them into a composite signal following a series of combination rules that are based on each relay’s channel quality.

For these types of low bandwidth applications, the relays will receive the same information from a common source transmitting on a single frequency (Freq0 in Figure 1). Relay re-transmissions are separated in frequency by using Frequency Division Multiple Access (FDMA) based techniques where each relay retransmits on a separate frequency (Freq1 – Freq4 in Figure 1). The transmitted bitstream will use a frame-based communication approach where the frame boundary defines frame and relay synchronization. While each received signal from each relay may be weak and distorted, it is the job of the receiver to combine these signals into one improved composite signal.

One main advantage of this tactical application compared with the commercial mobile industry is that we are not dealing with thousands of users at a time. But significant disadvantages of a tactical application involve:

- The logistics of fielding multiple, low-power relays versus having high-power cell tower infrastructure in place.
- Variable and longer relay distances versus having carefully sited cell towers relatively close together.
- Half-duplex communications versus the full-duplex communications common in commercial world, thus precluding a feedback channel for optimizing the RF link.

- No inherent time synchronization between relays (Note that our approach is not depending on GPS location or network time stamp, so sync must be included in frame structure) to facilitate combining of weak signals.

To overcome these disadvantages, the approach will focus most of the complexity at the receiver, not at the inexpensive relay.

The channel environments tested in this work are simulated on fading channel environments, both Rayleigh fading (e.g. urban area with no direct line of sight to the relay) and Rician fading (e.g. rural area with a direct line of sight to the relay). These degraded channels will have bit error rates (BER) up to 15%.

While it is possible to acquire channel synchronization at these high BERs, the amount of forward error control (FEC) needed, and thus channel overhead required, is extraordinarily high to give each individual channel adequate performance on its own. The goal of this work is to combine these individual channels in a way which improves the overall composite channel performance (as compared to the individual channels for the same BERs) and in doing so, minimize the amount of FEC needed on the individual channels.

To model the effect of various relay distances to the signal strength of the channel, the free-space path loss (L) formula in decibels is defined as:

$$L=20*\log_{10}(4\pi R / \lambda)$$

where R = distance, λ = wavelength, and

$$\lambda = v / f$$

where f = frequency of transmission and v = velocity of light speed $\sim 3 \times 10^8$ meters per second.

For example, given f = 75 MHz

$$\text{then } \lambda = (3 \times 10^8 \text{ m/s}) / 75 \times 10^6 = 4 \text{ meters}$$

Table 1 below gives some common values for free space path loss given transmission frequency is 75 MHz. Obviously as more loss is incurred at greater distances, the signal-to-noise ratio (SNR) of the channel gets weaker which causes the channel bit error rate to increase.

Table 1 Free space path loss based on distance of relay to destination at f = 75 MHz

R = distance (m)	λ = Wavelength (m)	Loss = $20\log_{10}(4\pi R / \lambda)$ (dB)
10000	4	89.9
25000	4	97.9
50000	4	103.9

In addition to path loss, there are also relative time shifts in the bitstream due to the varying transmission distances. The table below shows example bitstream delay amounts (bits) for relay distances of 10 km, 25 km, 50 km, given a 16000 bps channel.

The formula for the bit sample delay is:

Bit sample delay = (bitstream channel rate) * (R) / (v) where:

bitstream channel rate is given in bits per second (bps) (e.g. 16000 bps for a tactical radio channel)

R = distance given in meters (e.g. 10000, 25000, 50000 m)

v = light speed velocity $\sim 3 \times 10^8$ meters per second

The implication from Table 2 below is that while there are not large differences of the bitstream delay, it still must be measured and corrected for, and if relay distances change enough during a transmission, the bitstream delay can also drift.

Table 2 Bitstream bit delay based on relay distance

R = distance (m)	Channel rate (bps)	Bitstream bit delay = $\text{rate} * \text{distance} / \text{lightspeed}$ (bits)
10000	16000	0.53
25000	16000	1.33
50000	16000	2.66

3.2 Receiver Synchronization of Multiple Relay Signals

Enhancing communication performance using multiple relays depends on having good synchronization between the different relay signals at the receiver. The table above shows common delays attributed to distance. Since the relays themselves do not have synchronization, it must be taken care of at the receiver.

Each individual relay transmission must first achieve frame sync of the channel itself before the multiple relays can be aligned with each other. Common tactical channels have frame boundaries within the bitstream. Before these frames are sent, the receiver processes a bitstream preamble to determine frame sync.

An example of this synchronization technique is a newly developed standard tactical communication synchronization preamble frame that gives very reliable sync in 0.165 seconds (2636 bits in a 16000 bps channel). Modeling of the sync performance shows that reliable sync can be achieved at bit error rates (BER) even at 15%. After frame sync is achieved with the preamble, the receiver then keeps track of the bits within the frame, where a common tactical frame length for a 16000 bps channel is 360 bits or 22.5 ms.

3.3 Fading channel environments

Testing was performed using two fading channel scenarios considered for simulation, Rayleigh fading (e.g. marine in urban area with no direct line of sight to the relay) and Rician fading (e.g. marine in rural area or beach with a direct line of sight to the relay). These simulated channels were used to induce up to 15% BER on the baseband signals, which is the limit at which reliable channel synchronization can still be achieved for the signals being tested.

The assumption for this work is that possibly none of the relays give adequate channel performance on its own. This means that we cannot just use the mobile phone tower antenna model which selects the best tower and ignores the rest. The mobile phone tower model assumes that one of the signals is good enough, which we are not assuming to be the case.

Communications designs can ignore the effects of fading channels when the transmit power is always high enough to provide very high SNR which yields very few bit errors, even though the channel may occasionally undergo fading. Fades matter significantly more when the power levels are reduced, as is our case with the limited TX power on relays. Even if the relay could broadcast at high power levels, there may be instances where TX power is reduced to preserve battery life, so this work must address the effects of weak fading channels.

To combine these uncoordinated relay signals, there is an assumption that the bit error rate of the individual relay signals is low enough that frame synchronization can still be achieved. But as the previous section stated, robust synchronization can still be achieved up to 15% BER with a 0.165 s preamble in a modern tactical communications channel.

Because the individual relay channels fade at different instantaneous times, the goal is to combine a number of relay channels that are poor at different times in fading. In this way, we take advantage of the periods of good channel performance for each relay coming at different times. One goal may be to get performance where the vast majority of bit errors are eliminated through these techniques. But another goal could also be to just get overall performance to a level where a small amount of forward error control (FEC) with very limited overhead may be

able to easily correct the remaining bit errors. This two stage approach combines multiple relay redundancy along with a small amount of FEC redundancy.

As stated above, the relay signals are combined at the baseband signal (bitstream), not at the RF waveform. The baseband signal combining process requires that the fading channel performance be constantly determined by measuring individual bitstream bit error rate performance, rather than signal strength or quality. The following figures show graphs of BER performance. Note that since these graphs are plotting bit errors, the valleys are periods of good performance.

These graphs of bit errors help answer the question of how often to estimate errors in channel (both to the degree of fading and how quickly a channel goes in and out of fading).

- **Fading channel environment #1, Urban (Rayleigh fading), 16000 bps, 1 second graph**

- Figure 2 shows a chosen SNR=6.0 dB which yields ~10% BER overall,
- 8 to 10% BER is a level of bit errors which takes a very large overhead of FEC to attempt to correct most of the errors
- Each block is 0.01 second, which corresponds to 160 bits

- **Fading channel environment #2, Rural (Rician fading), 16000 bps, 1 second graph**

- Figure 3 shows chosen SNR=6.0 dB which yields ~8.5% BER overall
- similar looking characteristics of bit errors to the Rayleigh Fading
- slightly lower error rates than Rayleigh fading because of line-of-sight component in Rician fading

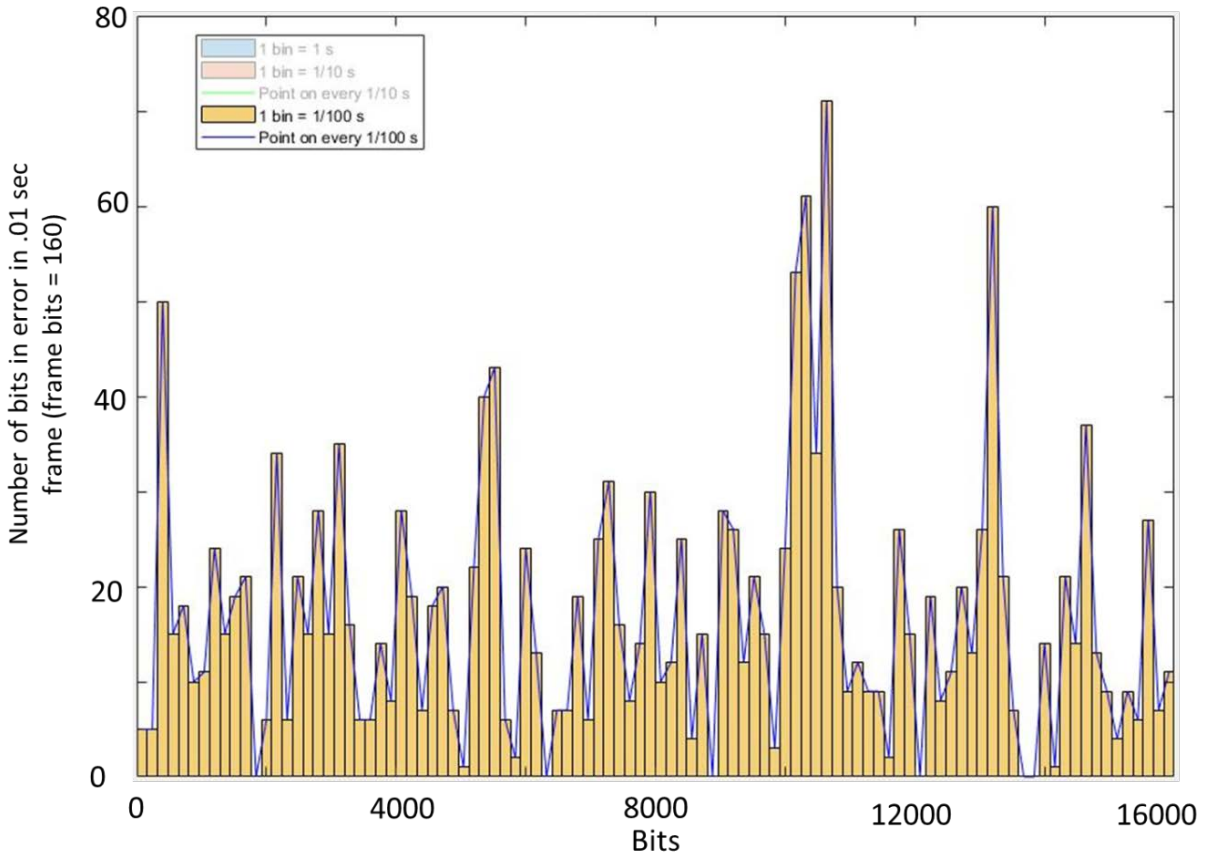


Figure 2 – Bit error plot of 0.01 second (160 bits) frames with fading channel environment #1, Urban (Rayleigh fading) channel at 16000 bps which yields overall ~10% BER at 6.0 dB SNR. Total graph shows 1.0 second.

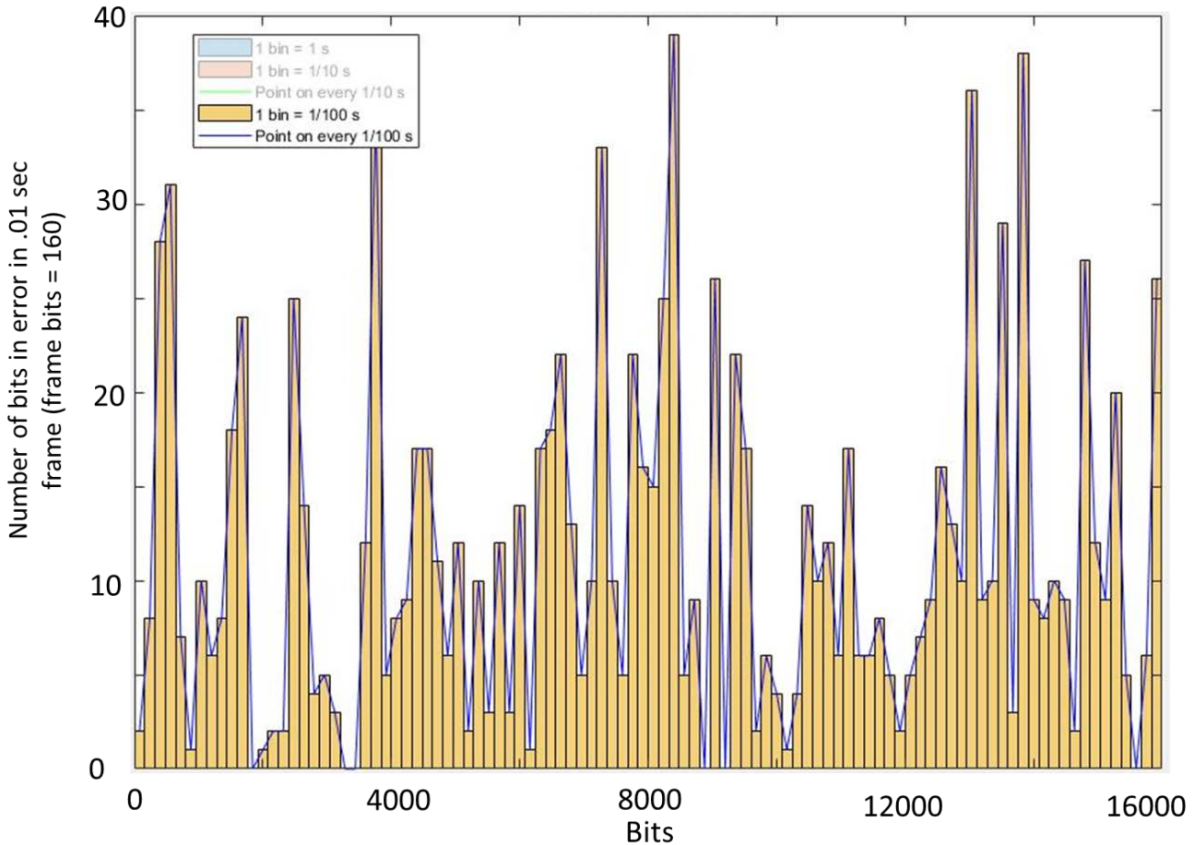


Figure 3 – Bit error plot of 0.01 second (160 bits) frames with fading channel #2, Rural (Rician fading), 16000 bps channel, which yields overall ~8.5% BER at 6.0 dB SNR. Total graph shows 1.0 second.

The bit error plots above show fading characteristics of channels as fades cause bit errors. The 1.0 second graphs in Figures 2 and 3 shows very large variability in BER over each 0.01 sec block. Each 0.01 s block is equivalent to 160 bits in the bitstream. The extreme variability shows each channel fluctuating between good and poor performance as the valleys (low bit error rate) represent good performance in the fading channel. The work here will show that combining relays with different periods of valleys (good performance) can achieve much improved overall performance.

Figures 2 and 3 above help determine how often bit error performance must be measured to track the fading characteristics of the channel. For reference, a common frame for 16000 bps tactical frames = 22.5 ms = 360 bits. The figures show that fading can occur as often as 0.01 seconds (160 bits). Conservatively, the receiver could measure the channel quality four times per frame, or every 90 bits, to adequately update the channel parameters. Later studies may focus on performance changes if we update the channel tracking parameters less conservatively at two times per frame or every 180 bits.

3.4 Signal combination techniques at receiver

Judging quality of channel

While the previous section showed how often to judge the quality of the channel, this section will explain how the quality of the channel is to be judged. One of the simplest ways to check for bit errors would be to just put in known dummy bits that the receiver could check for errors. Because these bits would only be used as a channel monitor and would be just wasted as an information source, the better approach is to use Forward Error Control (FEC) to monitor the condition of the channel.

The design will focus on periodically using strong FEC to not only protect the the sync and user ID bits in the frame header, but to also indicate the condition of the channel by monitoring the number of bits corrected in that header.

The FEC approach used is the Bose, Chaudhuri, Hocquenghem (BCH) code with five information bits supplemented by 10 error control bits. This approach is called a BCH(15,5) code because there are a total of 15 bits in the complete codeword, but only five of them are actual information bits. Our approach cannot use the BCH(15,5) code on the whole bitstream because of the significant overhead involved. Instead, it will be just used to measure the instantaneous channel condition and also to protect the header information. To summarize, the BCH(15,5) code has the following characteristics:

- BCH(15,5) uses 10 error control bits to protect 5 information bits
- BCH(15,5) algorithm corrects up to 3 errors of the 15 bits in the codeword
- BCH(15,5) algorithm also outputs number of bit errors = 0,1,2,3, or more
- Number of bit errors (0,1,2,3, or more) gives 5 different answers to channel quality
- *Use the number of bits in error to judge the quality of channel at that instant*

Channel quality update rate vs Overhead

The BER graphs in the previous section showed high error variability in only 160 bit blocks. If the design conservatively checks the condition of the channel every 90 bits, the computation for overhead shows that:

- Overhead rate using 10 error control bits in BCH (15,5) in each 90 bit sub-frame
= $10/90 = 11.1\%$
- This amount of overhead not only gives the channel condition but significantly protects header information from bit errors

- If channel condition was only checked two times per 360 bit frame, the overhead rate using 10 error control bits in BCH (15,5) in each 180 bit sub-frames = $10/180 = 5.55\%$

Relay bitstreams combination rules

In the initial portion of this work, various numbers of relays and various combination rules were tested. The most promising results showed significant improvement in the composite channel when using three relay channels. A second study showed what performance improvements could be achieved if two distant relays were used in addition to the three relays already used.

In every case, results showed that the linear combination of the relay channels yielded much better performance than only using the single best relay for any given sub-frame (as a mobile phone tower would use). Figure 4 below shows the linear combination rules for combining three relays. Combining five relays is similar in approach. The weights for each relay are given by the notation (W_1, W_2, \dots, W_n) where $N =$ the number of relays used.

A summary of the actual test parameters used is given in the next section.

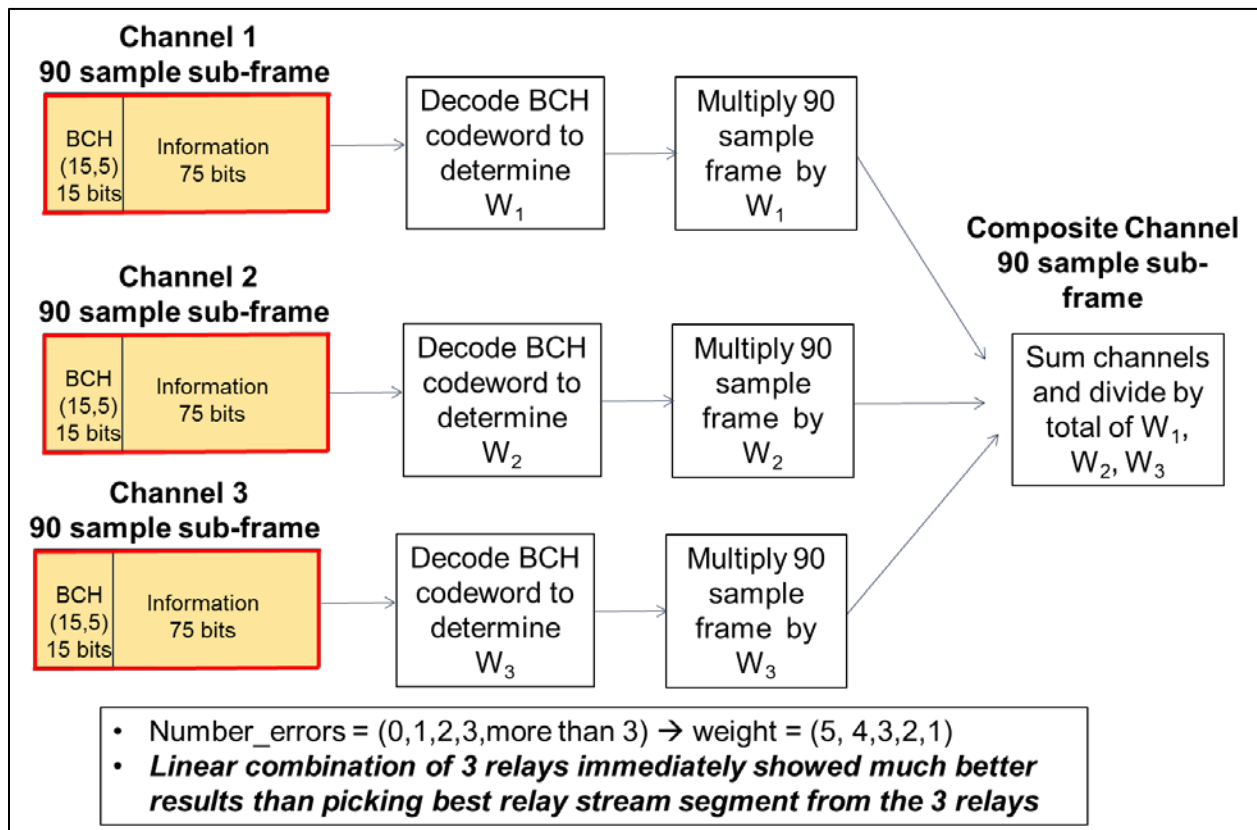


Figure 4 - Linear combination rules for combining three relays with the weights (W_1, W_2, W_3) determined by the BCH codeword in that bitstream's subframe. Combining five relays would be analogous.

3.5 Simulation of relay model, synchronization methods, communication methods, and signal combination techniques

The test design parameters for the channel from the relay to the destination receiver is given next. Each fading channel application scenario has two test conditions, one test with 3 relays, and one test with 2 distant relays added for a total of 5 relays.

Test Design parameters

- Fading conditions:
 - Application scenario 1: Urban (Rayleigh fading), 16000 bps channel
 - Application scenario 2: Rural (Rician fading), 16000 bps channel
- Number of Relays Present
 - Test condition 1: Three relays in use with varying SNR (distances)
 - Test condition 2: Five relays with the three relays from above test supplemented with two additional “far” relays
- Channel Frame structure
 - Figure 5 below shows a communications frame structure with 4 subheaders in 90 sample subframes spread throughout a 360 bit frame. BCH(15,5) error protection is used to protect the subheaders and count bit errors in each 15 bit codeword
 - For a 16000 bps channel, one 360 sample frame = 22.5 ms,
 - Four 90 sample subframes = 5.625 ms each
- Relay channel combination based on FEC weighting
 - BCH (15,5) reports 5 possible conditions for channel (0,1,2,3, or more bit errors in 15 bit codeword to judge the rest of that subframe)
 - Weighting based on mapping number of errors = (0,1,2,3,more than 3) to weights = (5,4,3,2,1) , e. g., 0 errors has a weight of 5.

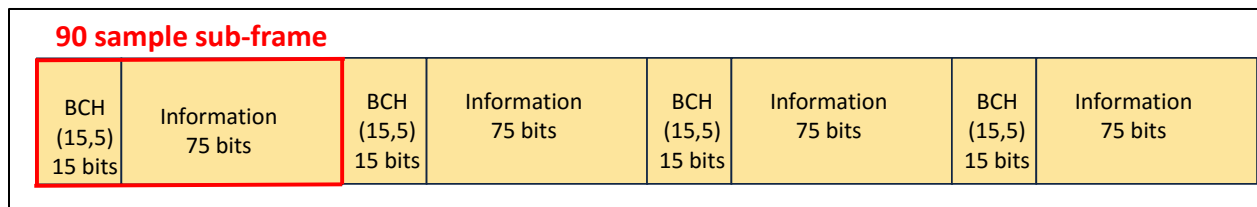


Figure 5 – Frame structure of a 360 bit frame with four BCH(15,5) codes giving status of channel and protecting these sub-headers.

4. Performance Analysis and Comparison

4.1 Results Introduction

The comprehensive test results are presented in the appendix at the end of this report. In all, results from 40 test conditions are presented there. There are two main sections based on the type of fading channel encountered. They are:

- Urban Fading Channel (Rayleigh) Bit Error Rates
- Rural Fading Channel (Rician) Bit Error Rates

Each section has results from combining bitstreams from three or five relays at varying SNR (distance) into an overall composite channel. The relay distances are defined by their signal-to-noise ratio (SNR)

- C=Close distance = 14.0 dB SNR (blue bar)
- M=Medium distance = 8.0 dB SNR (purple bar)
- F=Far distance = 4.5 dB SNR (red bar)

Table 3 below summarizes the conditions for the results given in the appendix. Note that for the cases of utilizing five total relays, the two additional relays are exclusively selected as “far” to judge what improvement may be achieved with additional weak signals.

Table 3 – 40 Test Conditions based on fading channel, relay distances for 3 relay test, relay distances for 5 relay test (C= close, M=medium, F=far distance)

Fading Channel Condition	3 Relay distances	5 Relay distances
Rayleigh or Rician	CCC	CCCF
Rayleigh or Rician	CCM	CCMFF
Rayleigh or Rician	CCF	CCFFF
Rayleigh or Rician	CMM	CMMFF
Rayleigh or Rician	CMF	CMFFF
Rayleigh or Rician	CFF	CFFFF
Rayleigh or Rician	MMM	MMMFF
Rayleigh or Rician	MMF	MMFFF
Rayleigh or Rician	MFF	MFFFF
Rayleigh or Rician	FFF	FFFFF

4.2 Results Evaluation

- ***In the case of 3 relays all with good channel quality (14.0 dB SNR), the composite channel can be made into an almost error free channel:*** For example, when 3 relays have BER in the 1.5 to 2.2% range, the resultant composite BER in both the urban and rural fading channel was approximately 0.1%.
- ***In the case of 3 relays all with medium channel quality (8.0 dB SNR), the composite channel can be combined into a much improved channel:*** For example, when 3 relays have BERs in the 5.0 to 7.5% range, combining them can give a composite channel in the 1.0 to 2.2% BER range.
- ***In the case of 3 relays all with poor channel quality (4.5 dB SNR), the composite channel error rate was reduced by more than half of the individual poor channel error rates.*** For example, when bit error rates were in the 12.0 – 13.5% range, the composite error rate was in the 5.4 to 5.8% range.
- ***In the case of 3 relays with only one good channel, the composite channel is not significantly harmed by the 2 poor relay channels:*** For example, in both the urban and rural fading channel environments, the performance of the composite channel was very close to the performance of the closest relay, even when the two other channels had error rates greater than 10%.
- ***In the case of 5 relays, adding 2 distant channel relays to 3 others significantly improves performance if the other relay channels are also poor:*** For example, the BERs of the composite channel for using 5 distant channels was approximately half the rate of only using 3 distant relay channels for both the urban and rural fading channel environments.
- ***In the case of 5 relays, adding 2 distant channel relays to 3 others does not hurt performance if the other relay channels are already strong:*** For example, in each

fading channel environment, using 3 strong relays or using 3 strong relays with 2 distant relays both yielded an almost error free composite channel.

5. Conclusion and Future Research

The results of this research show that the robustness of a beyond line of sight (BLOS) communications link can be improved without relying on satellites, piloted aircraft, or expensive drones. Instead such a system can leverage multiple (three or more) relays with minor enhancements to existing radio systems by improving their receiver capabilities. Additionally, such a robust link can support lower transmitter power levels thus enabling the users to reduce their battery consumption rate. Future research possibilities lie in three main areas. They are:

5.1 Channel Measurement Update Rates

One possibility for future tests is in refining channel measurement update rates for bitstream based on performance. In all presented tests, the channel was measured four times a frame, or every 90 bits. This new study would be to study the performance differences if the channel measurement was only performed two times a frame, or every 180 bits. While the overhead rate using 10 error control bits in 90 bit sub-frames is 11.1% (10/90), the overhead rate using 180 bit sub-frames could be cut in half to 5.55% (10/180).

5.2 Channel Quality Calculation

Another possibility for future tests is in changing how the BCH code at beginning of each subframe is the only BCH code used in the determination of the rest of the sub-frame's weighting. The main advantage to this approach is that each sub-frame is completely self-contained which means that there is no delay in processing each sub-frame.

A possible new approach would be to average every two consecutive BCH code weightings for the 75 information bits in between. Figure 6 below shows the two possibilities. The main advantage to this approach is possibly better performance if the approach is judging the channel quality at both sides of the 75 information bits in the subframe. The disadvantage is that this approach causes the whole frame to be delayed at the receiver because the fourth sub-frame now depends on the next frame's first BCH code determination. A study to determine if the possible performance improvements would justify the frame delay encountered at the receiver would be valuable.

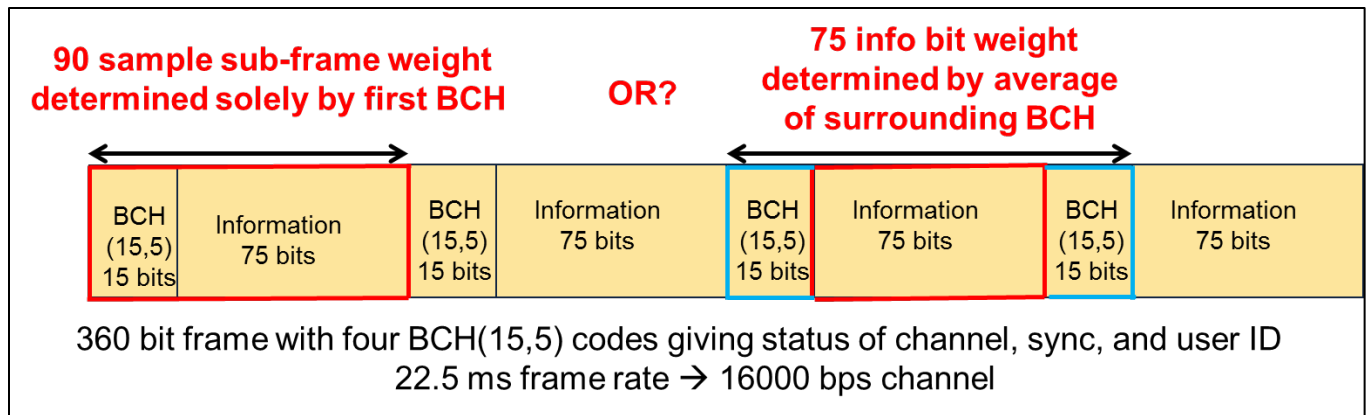


Figure 6 – Comparison between determining weighting channel condition with one BCH code or by averaging the weighting by two surrounding BCH codes.

5.3 Transforming Simulations into Live Tests

Finally, the next goal is to investigate these simulated techniques with actual hardware. Even if the receiver cannot process the multiple relays into the composite channel in real time, much progress will be gained in getting live transmitted relay channel signals received and processed offline, instead of using simulated MATLAB fading channels.

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A Appendix Results

A.1 Results Introduction

The comprehensive test results are presented in this appendix. There are two main sections based on the type of fading channel encountered. They are:

- Urban Fading Channel (Rayleigh) Bit Error Rates
- Rural Fading Channel (Rician) Bit Error Rates

Each section has 10 figures of the resultant bit error rates from three relays at varying SNR (distance) compared with results from combining five relays. Note that for the cases of utilizing five total relays, the two additional relays are exclusively selected as “far” to judge what improvement may be achieved with additional weak signals.

The relays each have three possible distances designated by the SNR and graphically shown by their color. The distances are defined by

- C=Close distance = 14.0 dB SNR (blue bar)
- M=Medium distance = 8.0 dB SNR (purple bar)
- F=Far distance = 4.5 dB SNR (red bar)

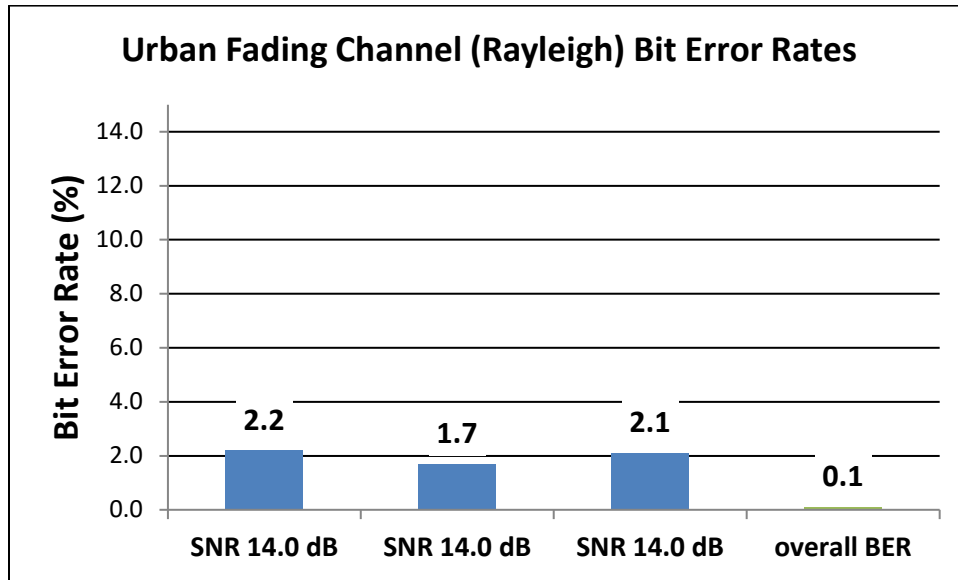
The overall composite BER of the weighted sum of the relays is shown by the green bar.

The table below summarizes the conditions for the results given in the appendix.

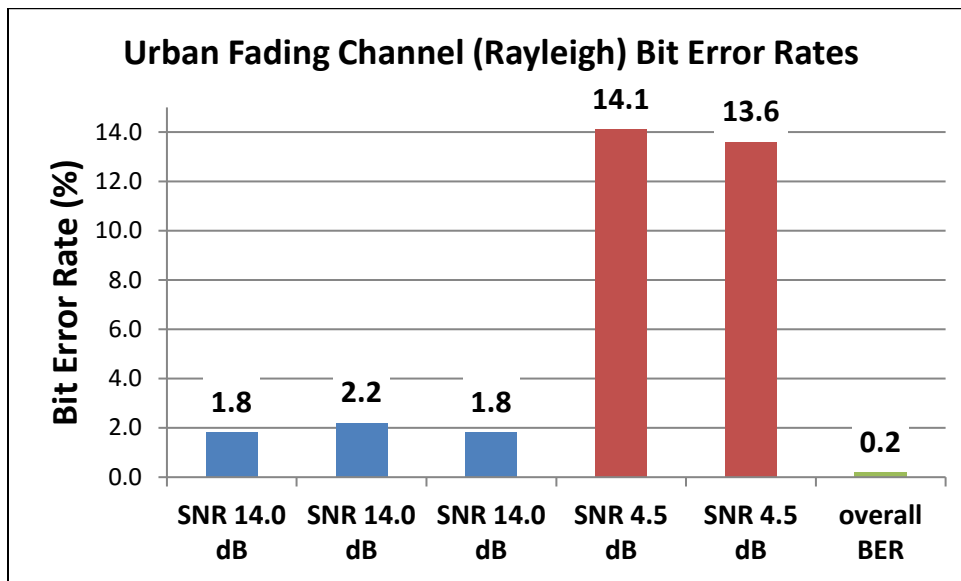
Table 4 – 40 Test Conditions based on fading channel, relay distances for 3 relay test, relay distances for 5 relay test (C= close, M=medium, F=far distance)

Fading Channel Condition	3 Relay distances	5 Relay distances
Rayleigh or Rician	CCC	CCCFF
Rayleigh or Rician	CCM	CCMFF
Rayleigh or Rician	CCF	CCFFF
Rayleigh or Rician	CMM	CMMFF
Rayleigh or Rician	CMF	CMFFF
Rayleigh or Rician	CFF	CFFFF
Rayleigh or Rician	MMM	MMMFF
Rayleigh or Rician	MMF	MMFFF
Rayleigh or Rician	MFF	MFFFF
Rayleigh or Rician	FFF	FFFFF

**A.2 Urban Fading Channel (Rayleigh) Bit Error Rates Comparing 3 Relays to 5 Relays
(with 2 “far” relays added)**

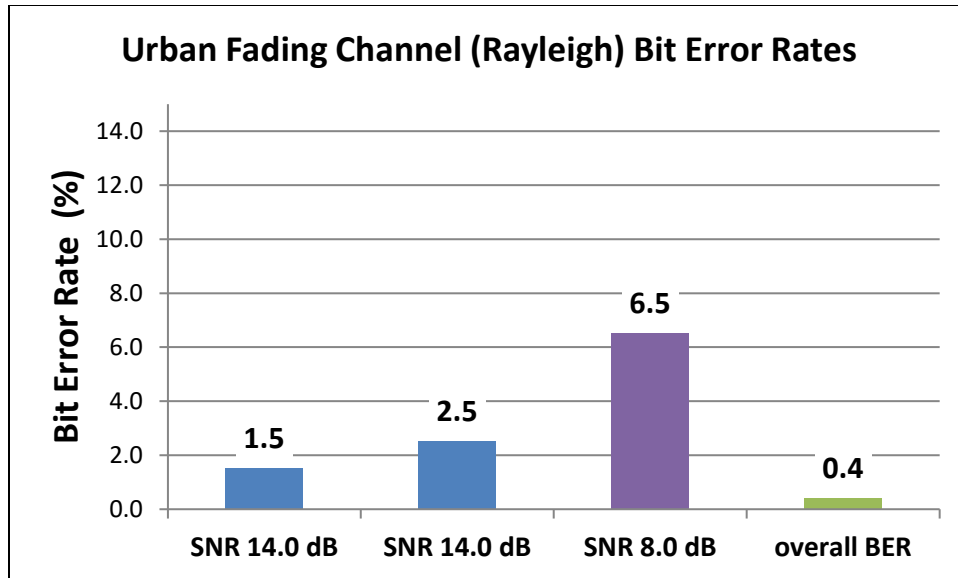


(a) 3 relays

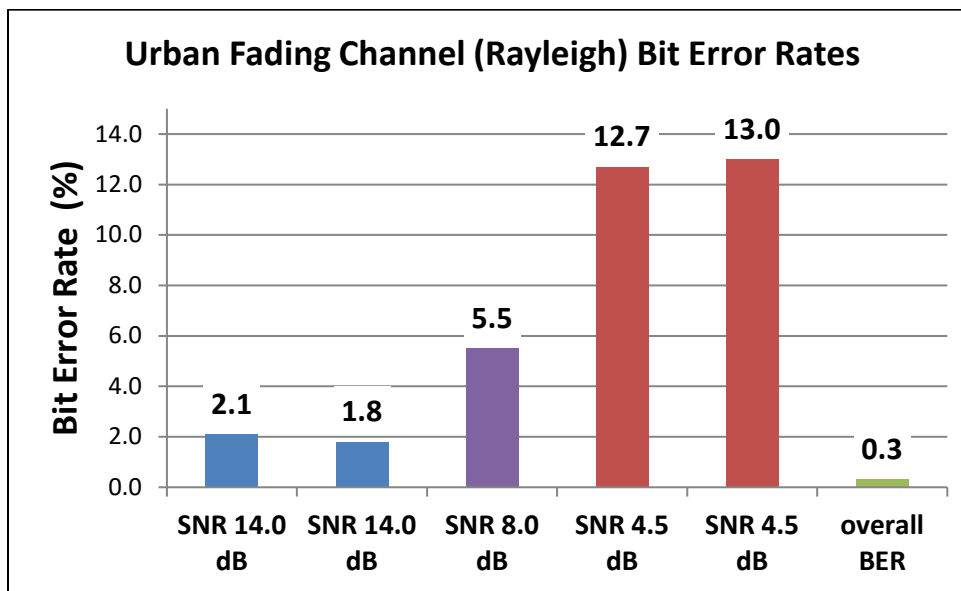


(b) 5 relays

Figure 7 – Urban channel, 3 relays (close, close, close) vs. 5 relays (close, close, close, far, far)

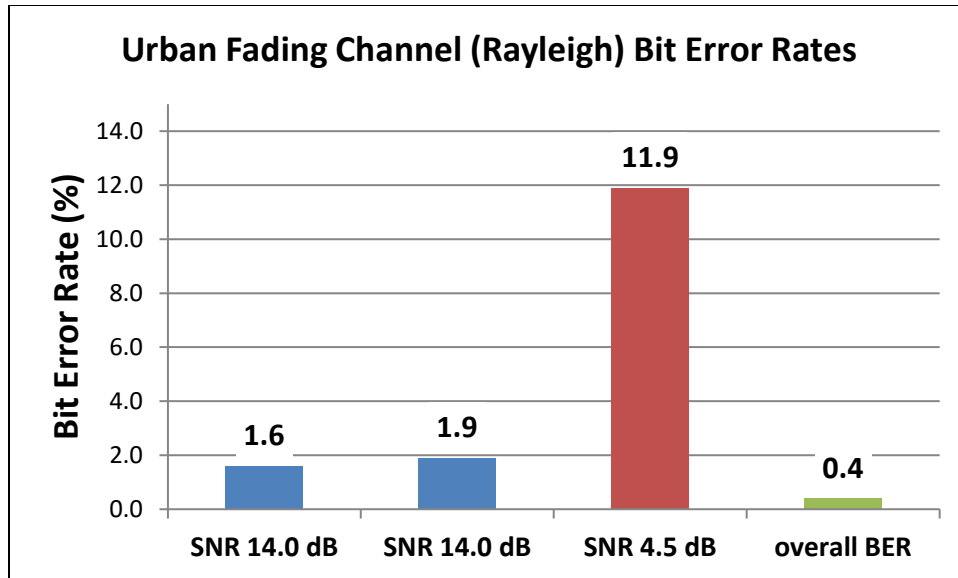


(a) 3 relays

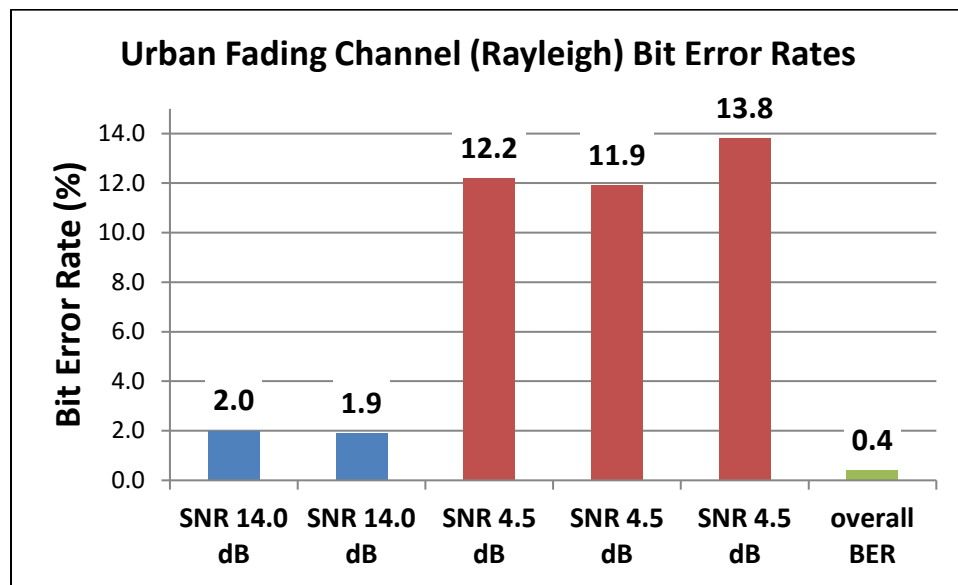


(b) 5 relays

Figure 8 – Urban channel, 3 relays (close, close, medium) vs. 5 relays (close, close, medium, far, far)

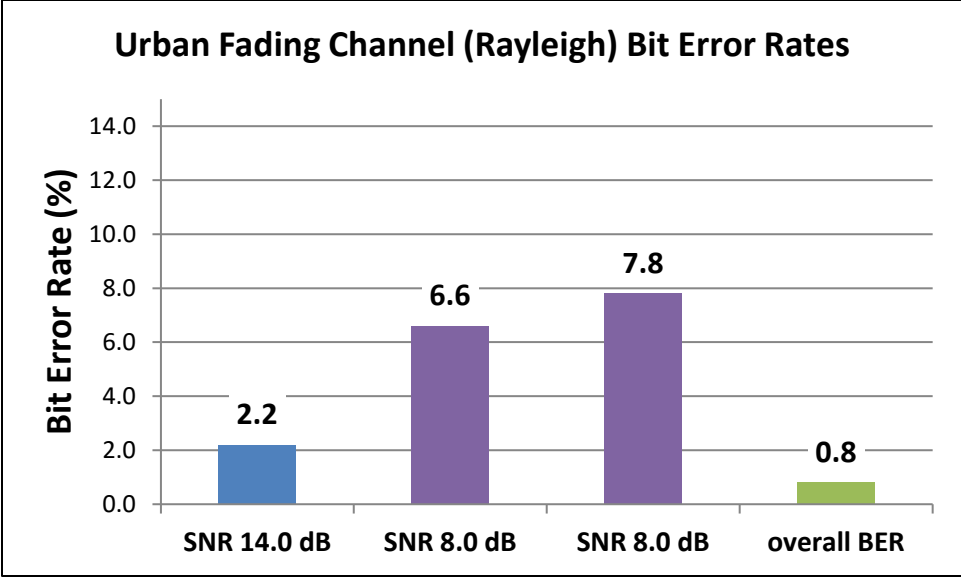


(a) 3 relays

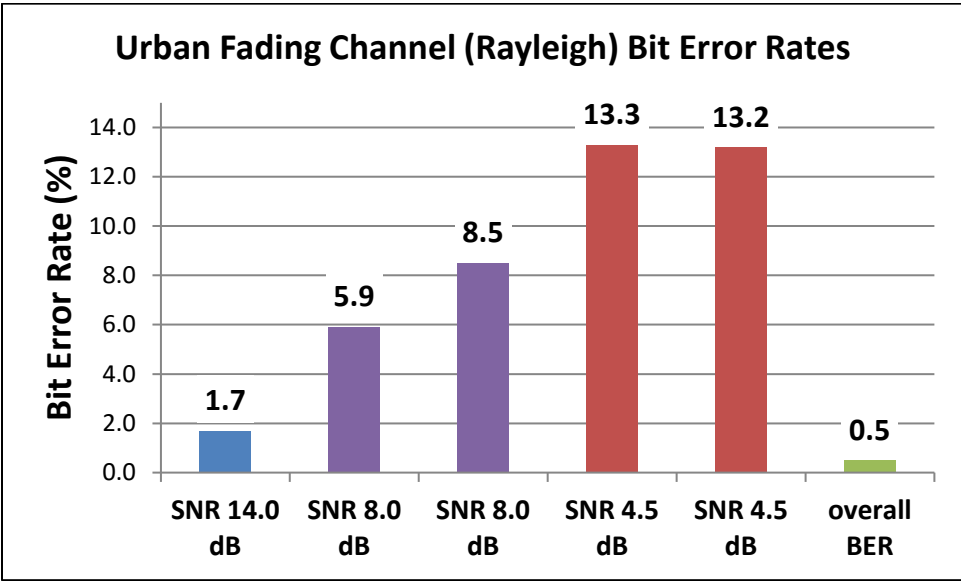


(b) 5 relays

Figure 9 – Urban channel, 3 relays (close, close, far) vs. 5 relays (close, close, far, far, far)

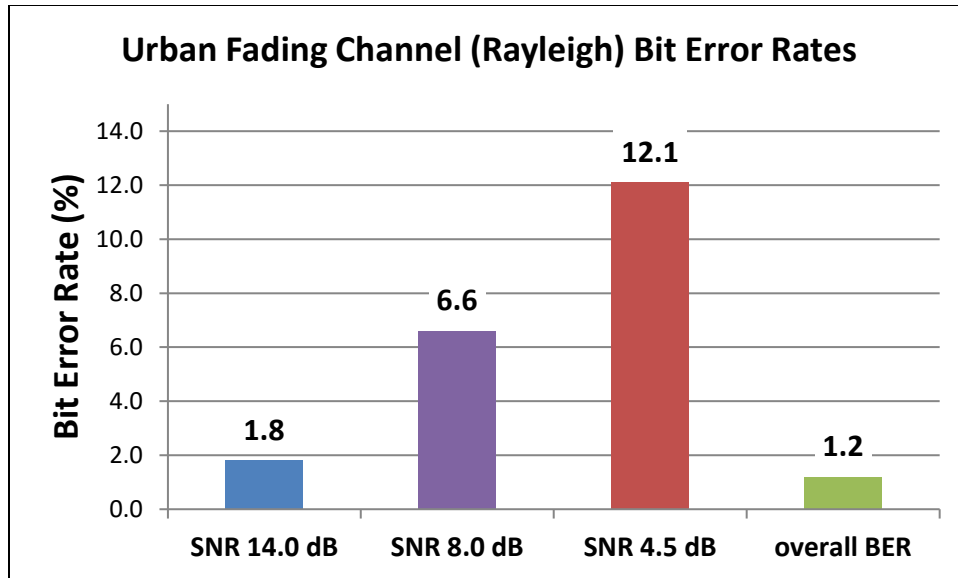


(a) 3 relays

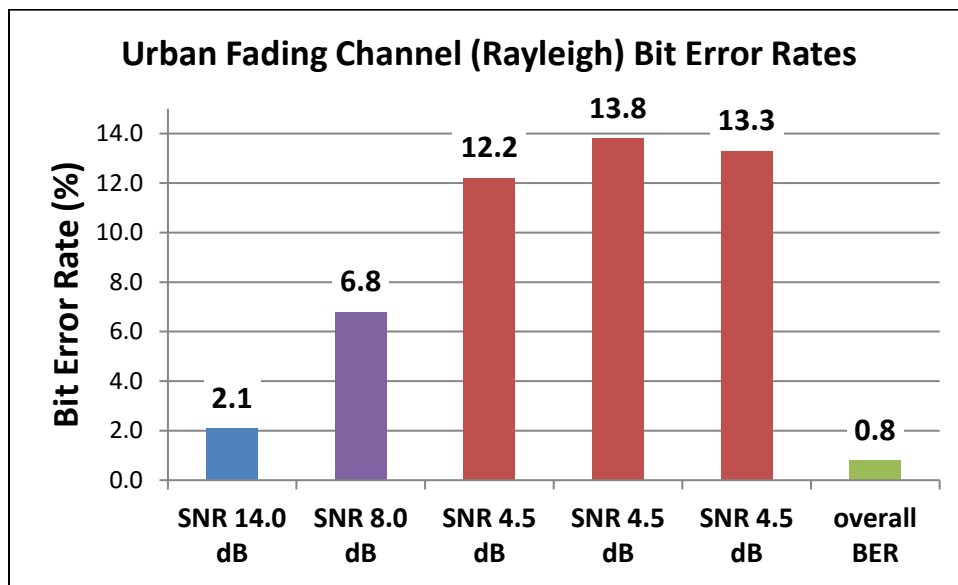


(b) 5 relays

Figure 10 – Urban channel, 3 relays (close, medium, medium) vs. 5 relays (close, medium, medium, far, far)

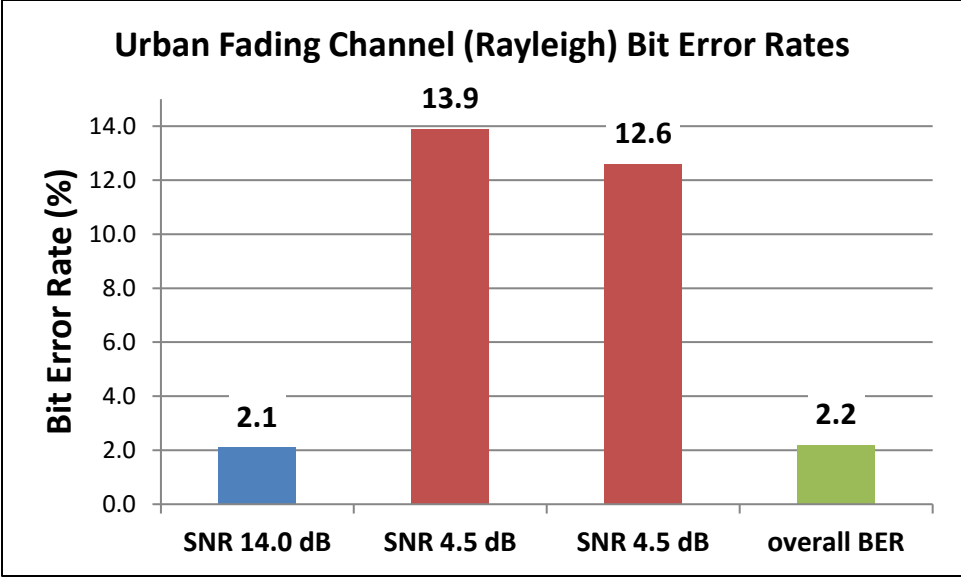


(a) 3 relays

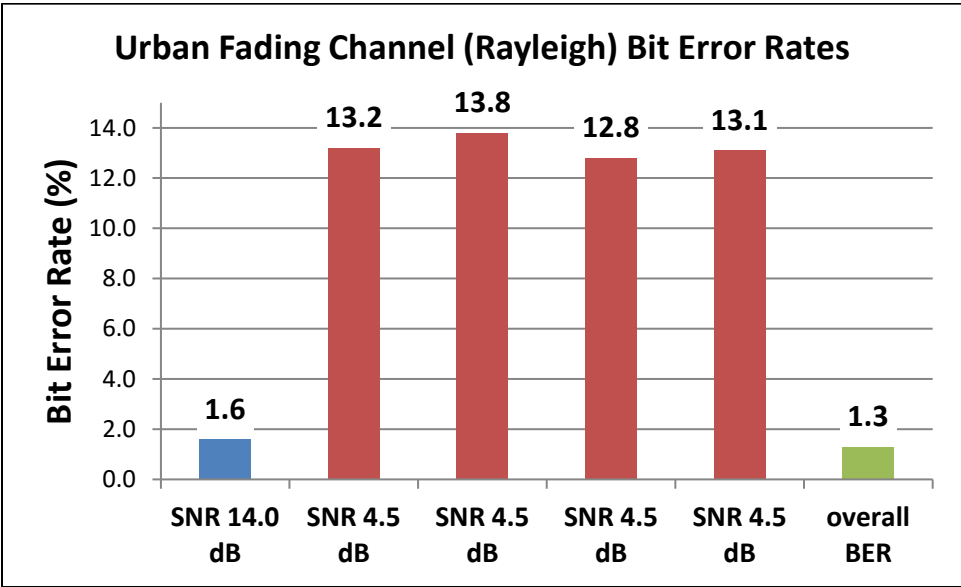


(b) 5 relays

Figure 11 – Urban channel, 3 relays (close, medium, far) vs. 5 relays (close, medium, far, far, far)

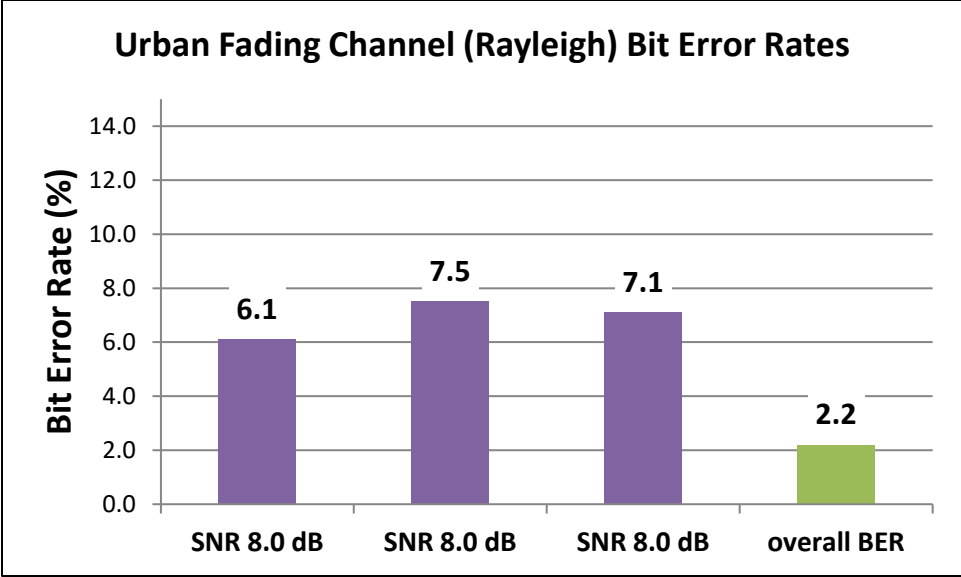


(a) 3 relays

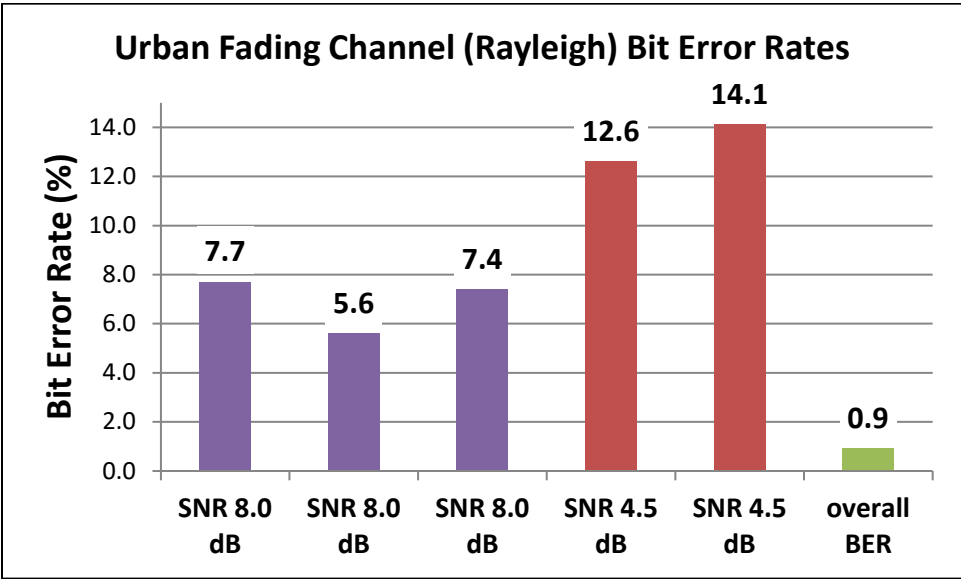


(b) 5 relays

Figure 12 – Urban channel, 3 relays (close, far, far) vs. 5 relays (close, far, far, far, far)

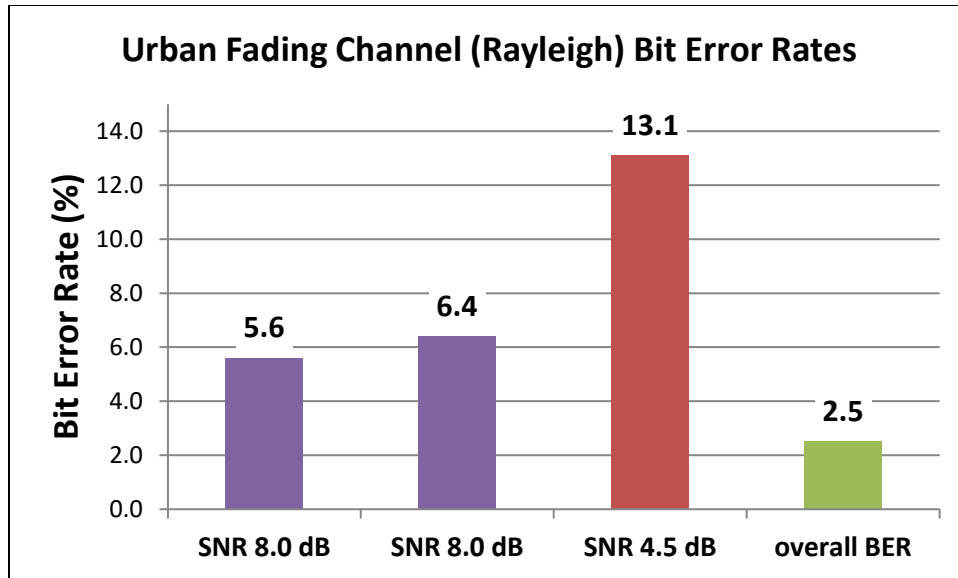


(a) 3 relays

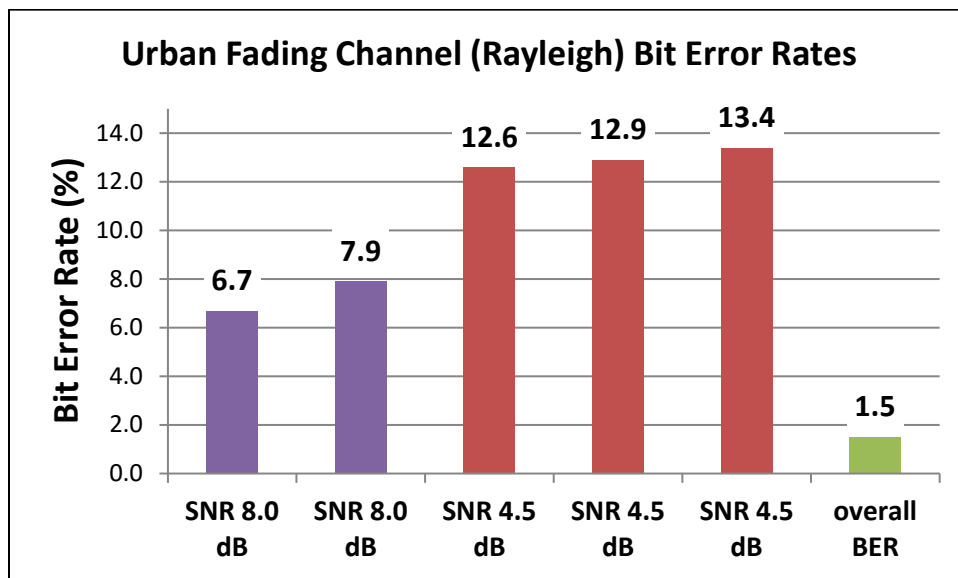


(b) 5 relays

Figure 13 – Urban channel, 3 relays (medium, medium, medium) vs. 5 relays (medium, medium, medium, far, far)

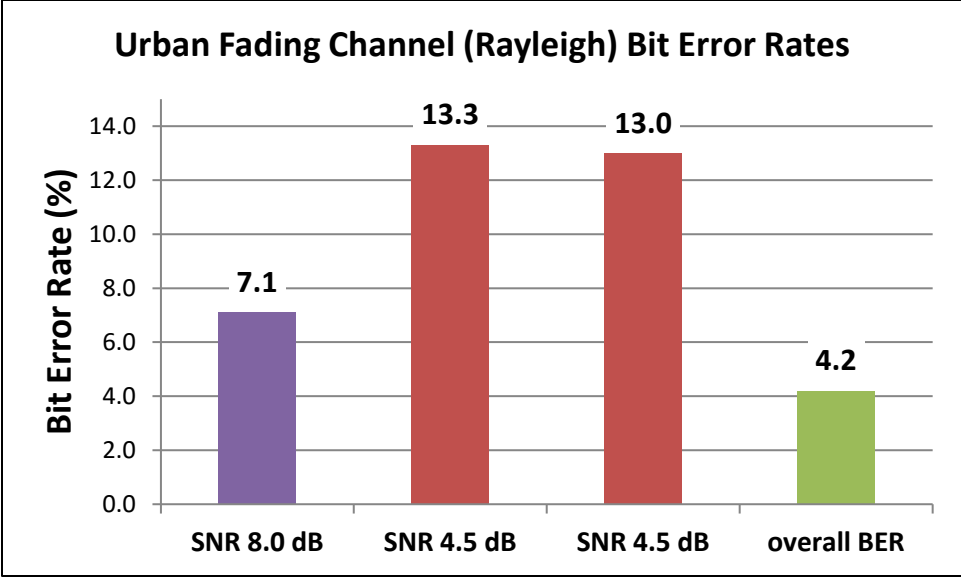


(a) 3 relays

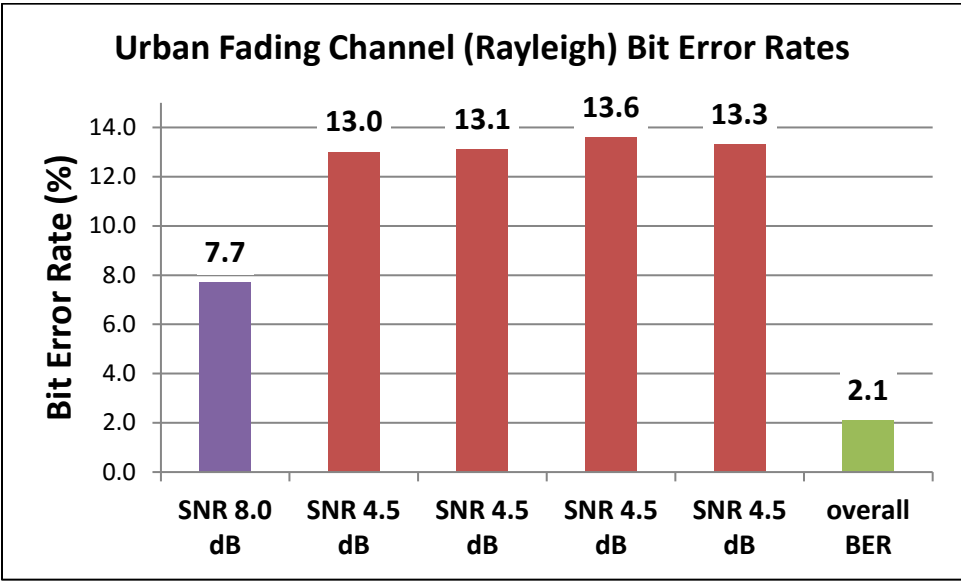


(b) 5 relays

Figure 14 – Urban channel, 3 relays (medium, medium, far) vs. 5 relays (medium, medium, far, far, far)

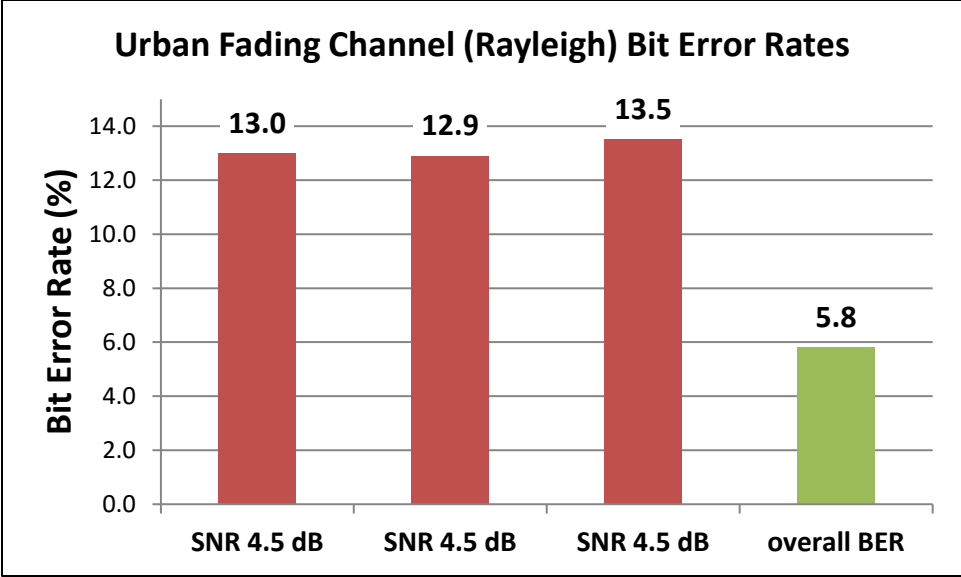


(a) 3 relays

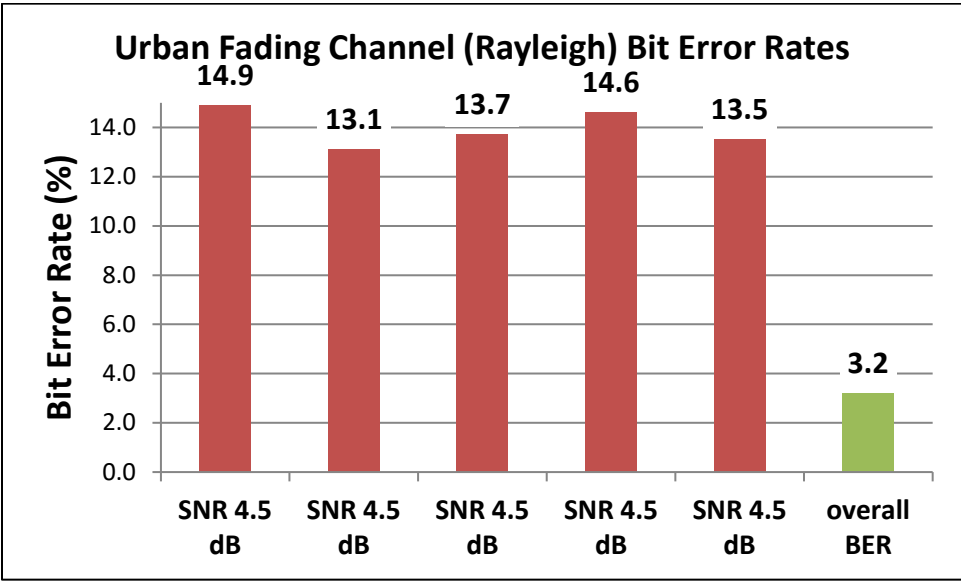


(b) 5 relays

Figure 15 – Urban channel, 3 relays (medium, far, far) vs. 5 relays (medium, far, far, far, far)



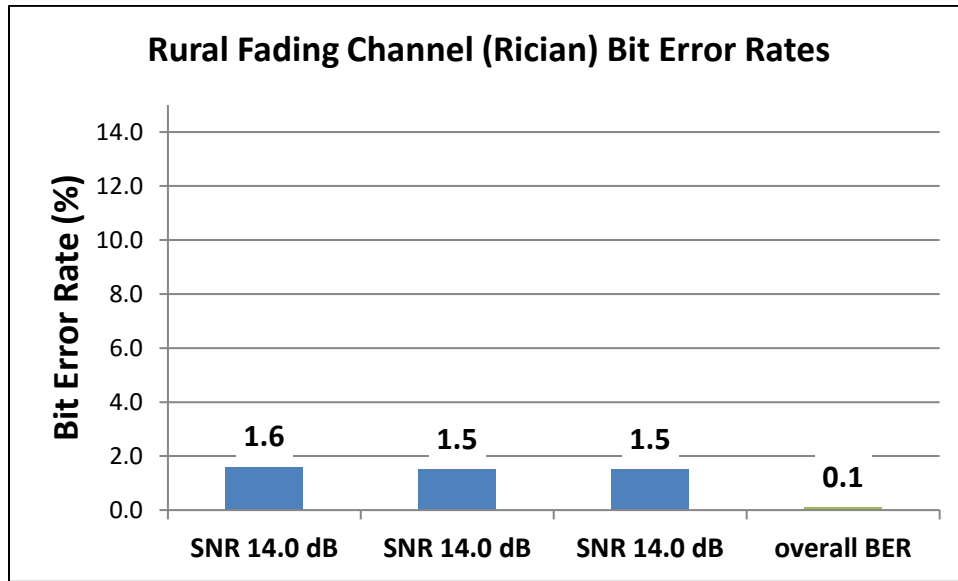
(a) 3 relays



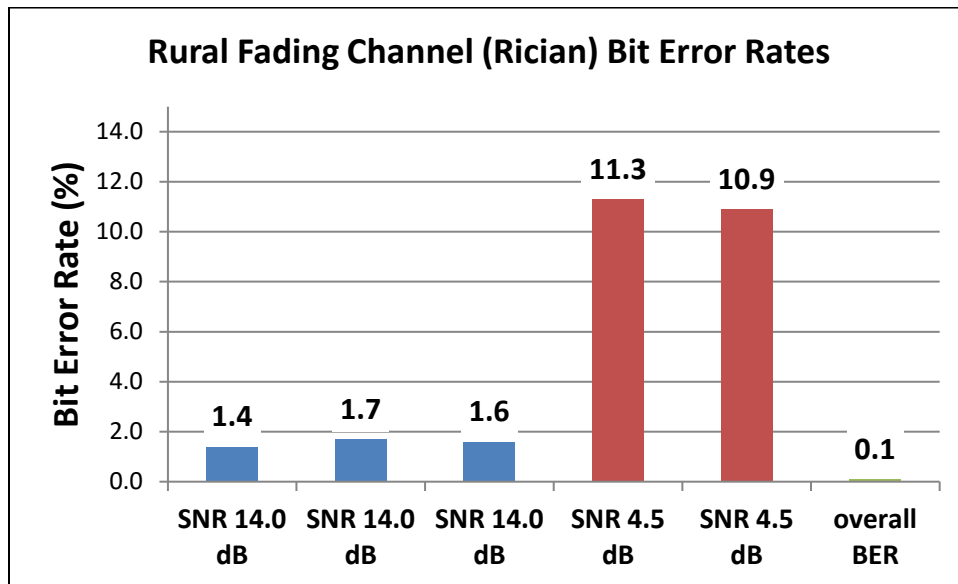
(b) 5 relays

Figure 16 – Urban channel, 3 relays (far, far, far) vs. 5 relays (far, far, far, far, far)

A.3 Rural Fading Channel (Rician) Bit Error Rates Comparing 3 Relays to 5 Relays (with two “far” relays added)

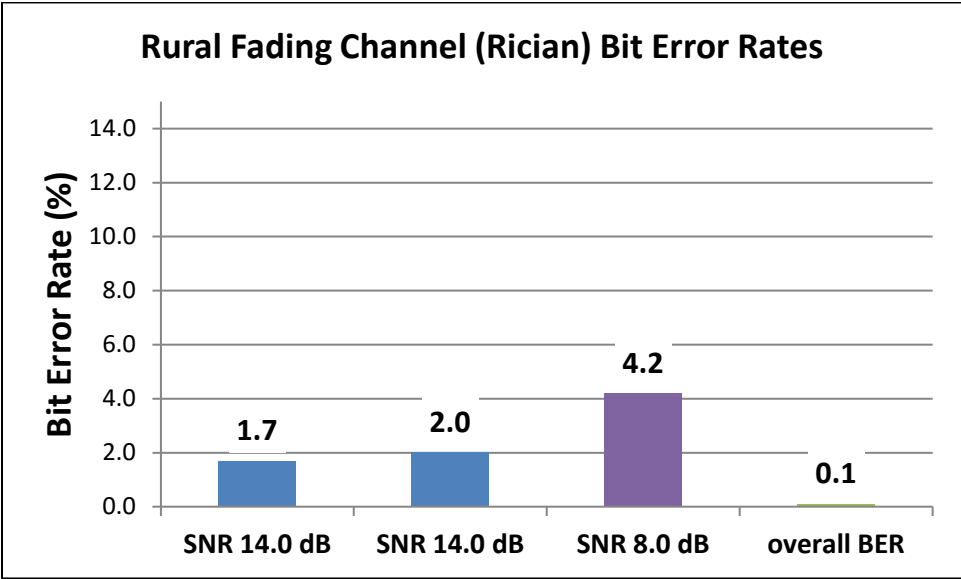


(a) 3 relays

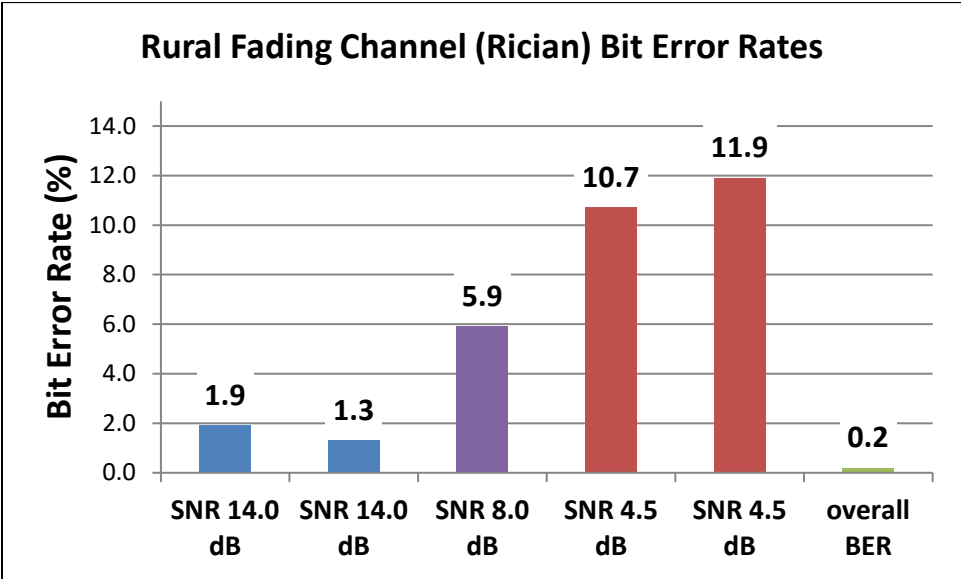


(b) 5 relays

Figure 17 – Rural channel, 3 relays (close, close, close) vs. 5 relays (close, close, close, far, far)

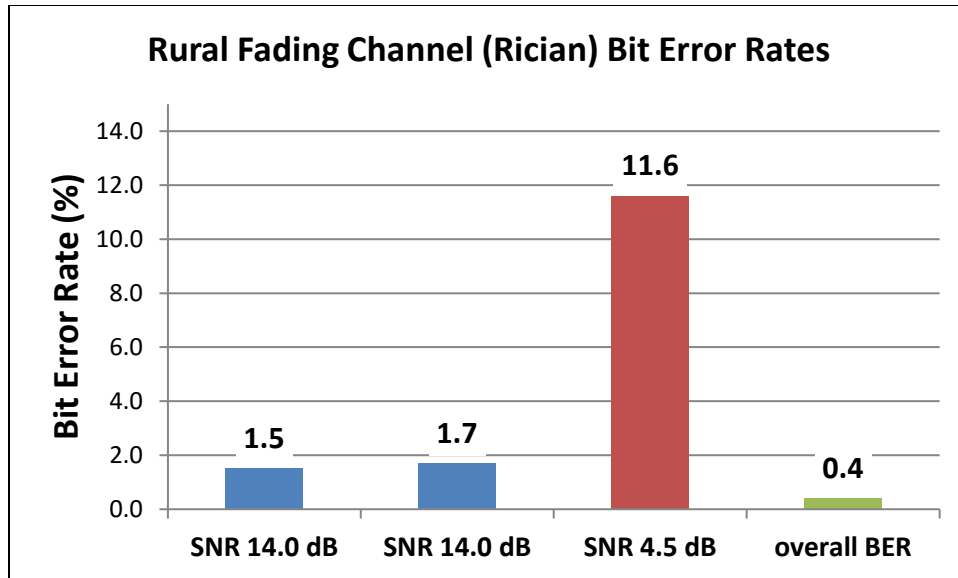


(a) 3 relays

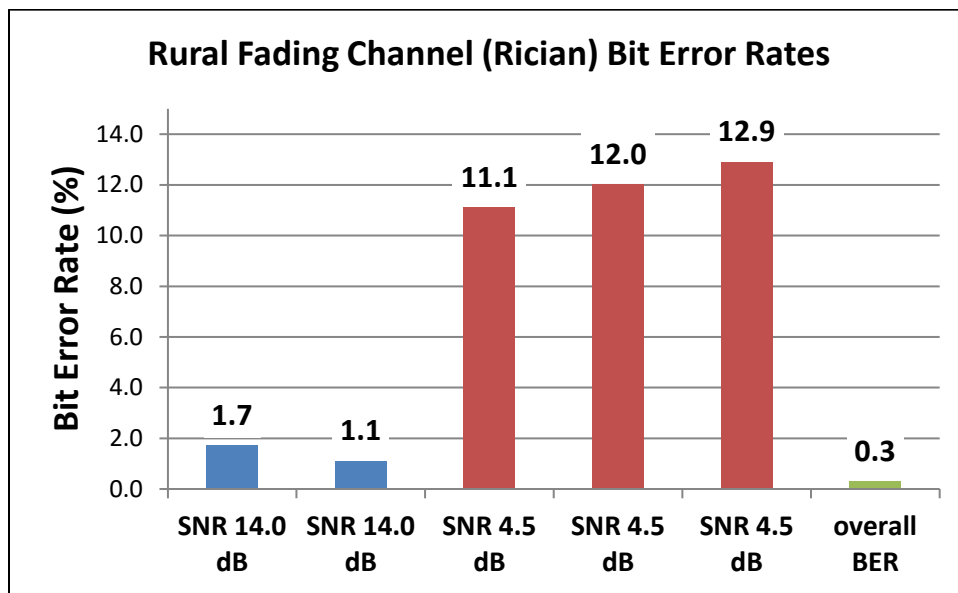


(b) 5 relays

Figure 18 – Rural channel, 3 relays (close, close, medium) vs. 5 relays (close, close, medium, far, far)

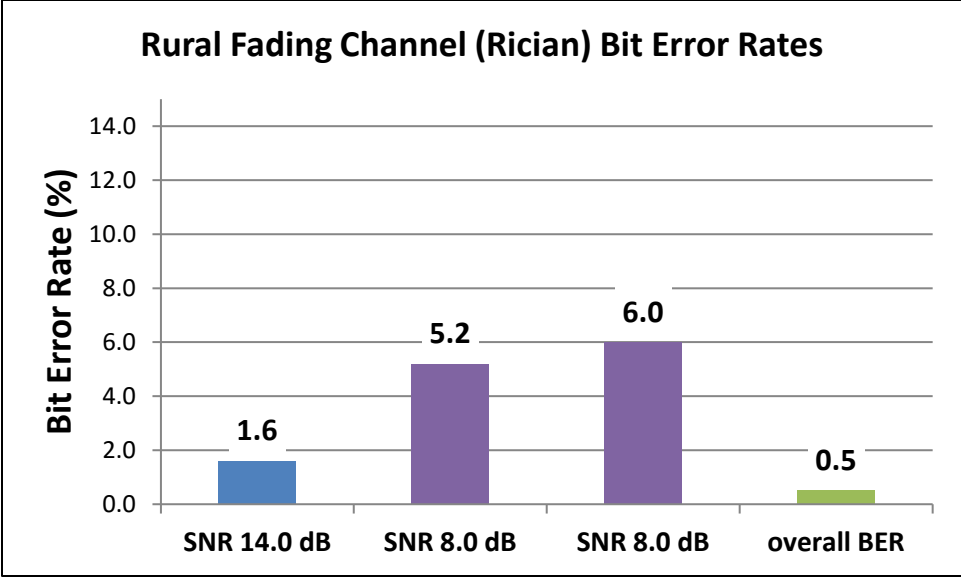


(a) 3 relays

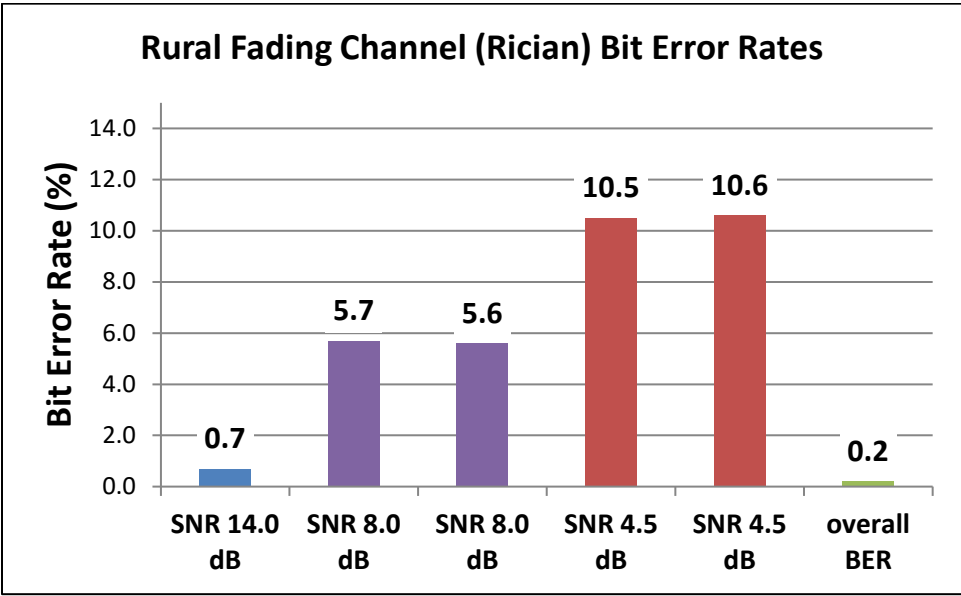


(b) 5 relays

Figure 19 – Rural channel, 3 relays (close, close, far) vs. 5 relays (close, close, far, far, far)

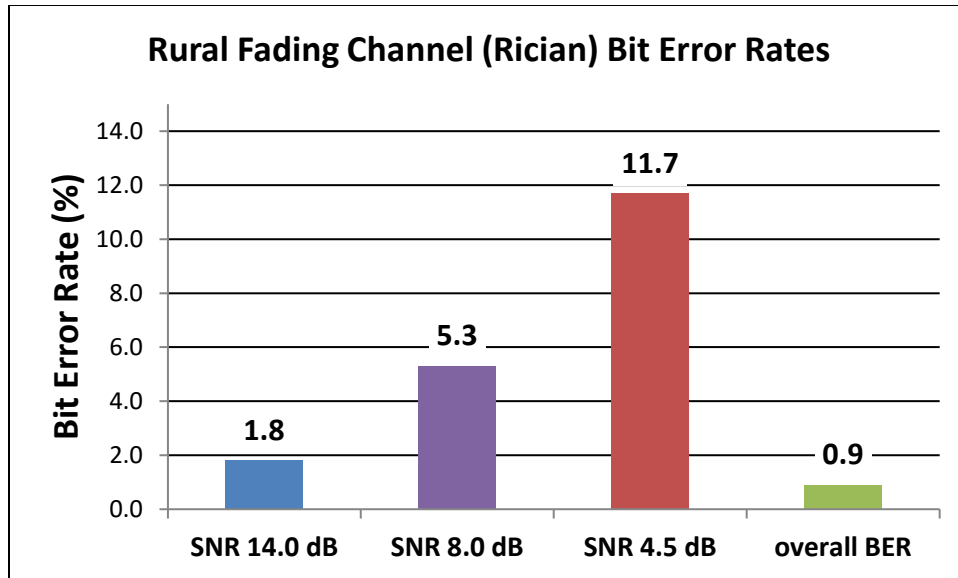


(a) 3 relays

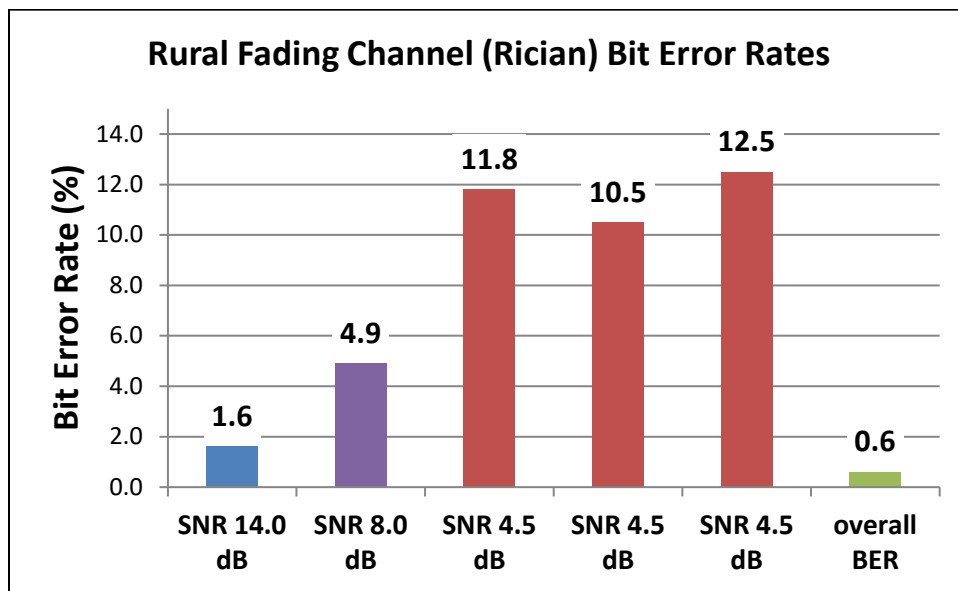


(b) 5 relays

Figure 20 – Rural channel, 3 relays (close, medium, medium) vs. 5 relays (close, medium, medium, far, far)

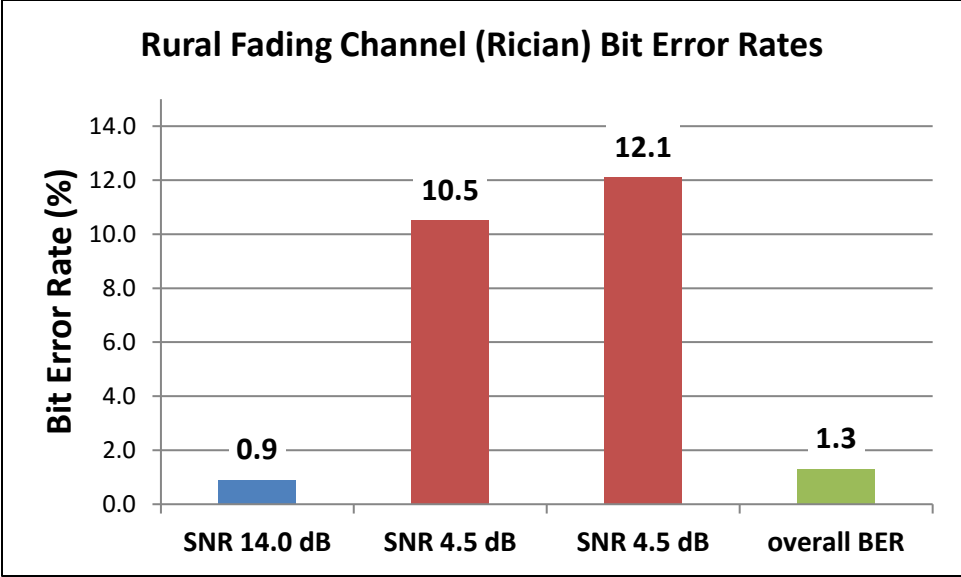


(a) 3 relays

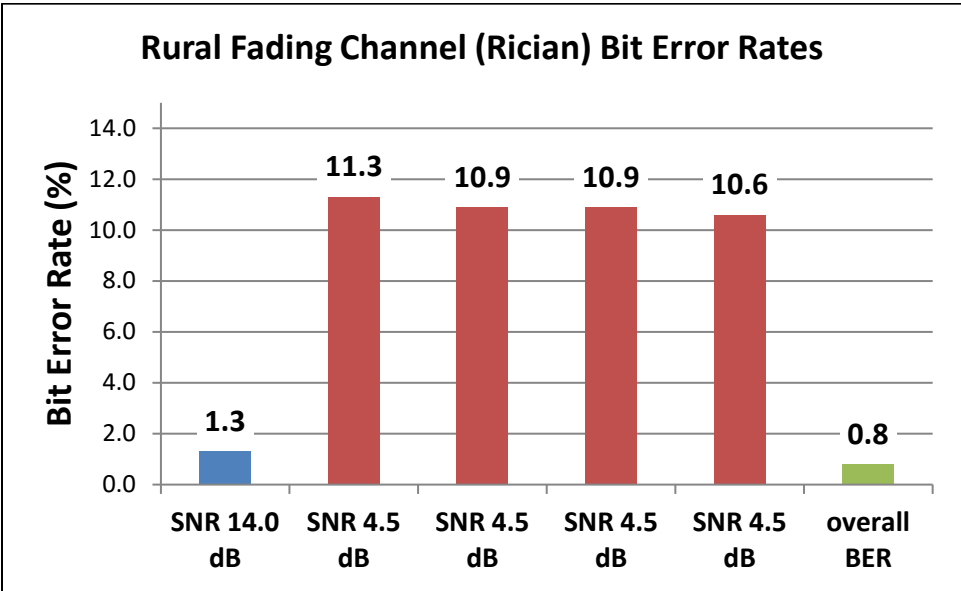


(b) 5 relays

Figure 21 – Rural channel, 3 relays (close, medium, far) vs. 5 relays (close, medium, far, far, far)

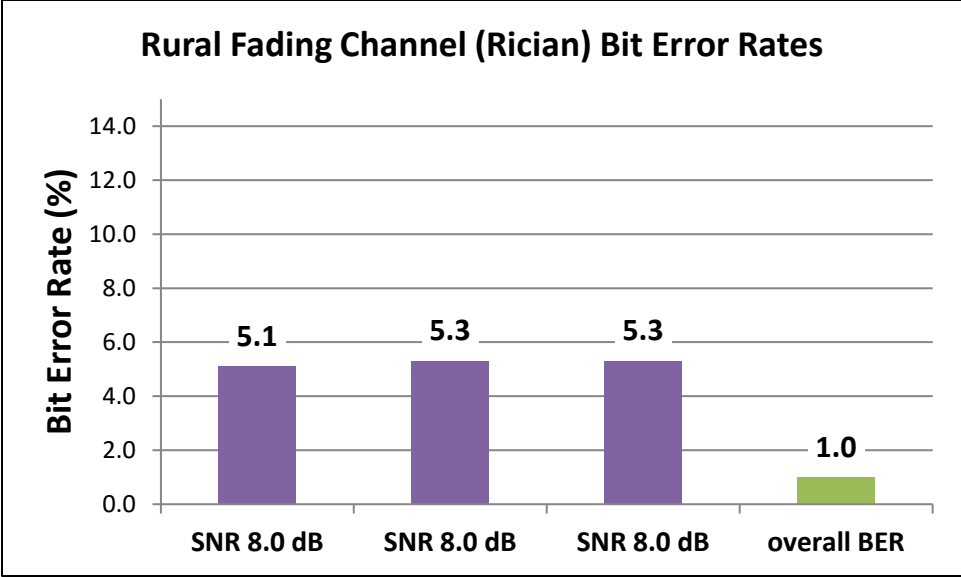


(a) 3 relays

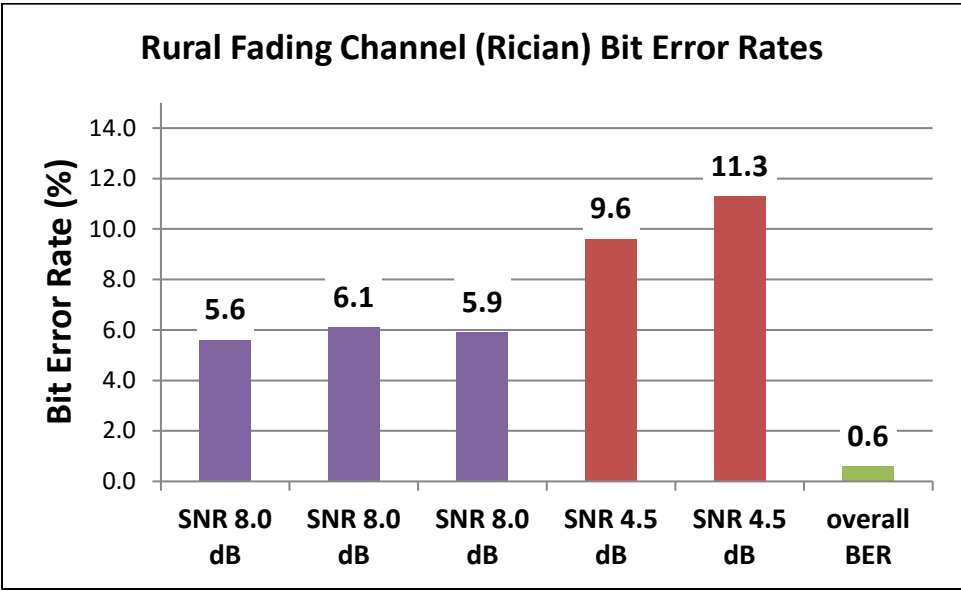


(b) 5 relays

Figure 22 – Rural channel, 3 relays (close, far, far) vs. 5 relays (close, far, far, far, far)

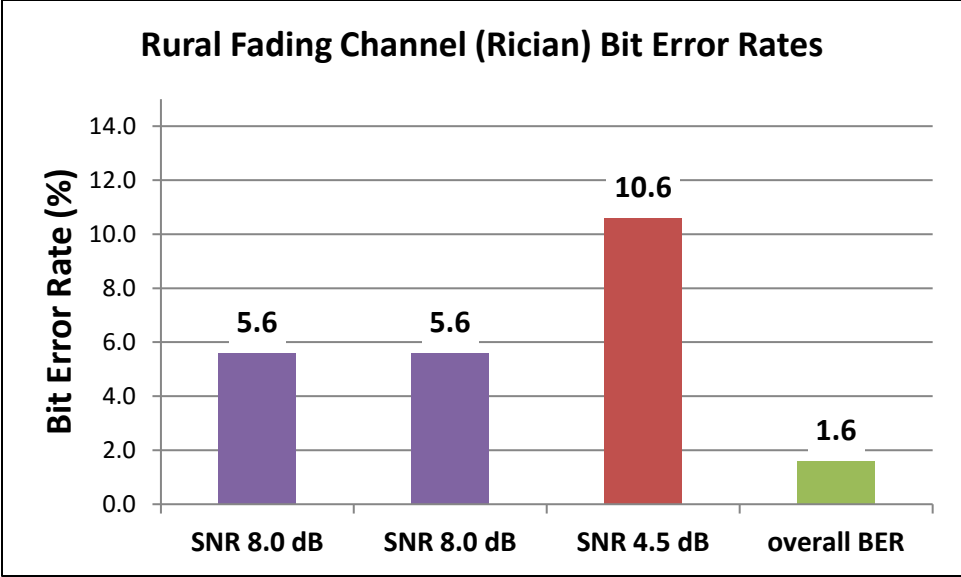


(a) 3 relays

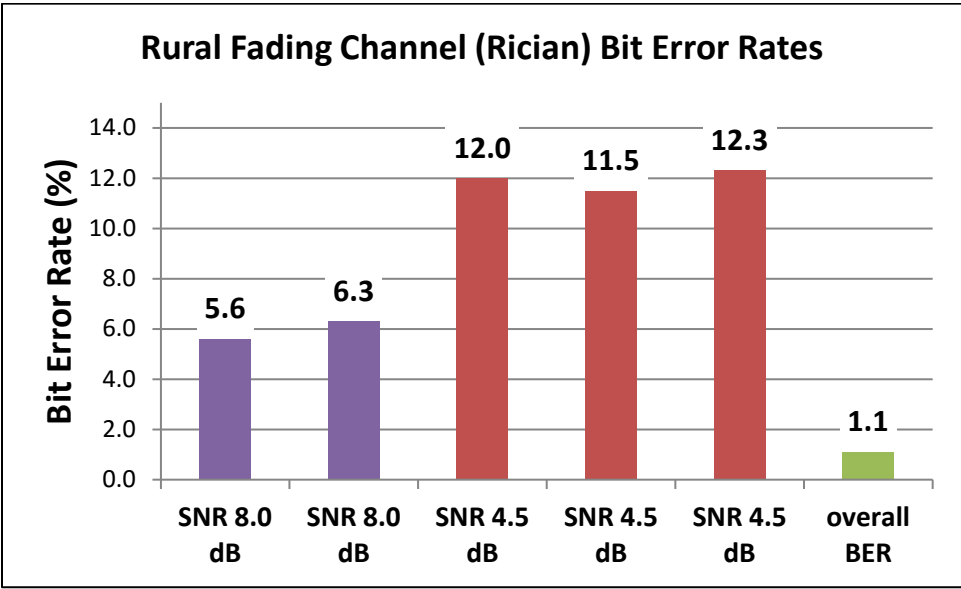


(b) 5 relays

Figure 23 – Rural channel, 3 relays (medium, medium, medium) vs. 5 relays (medium, medium, medium, far, far)

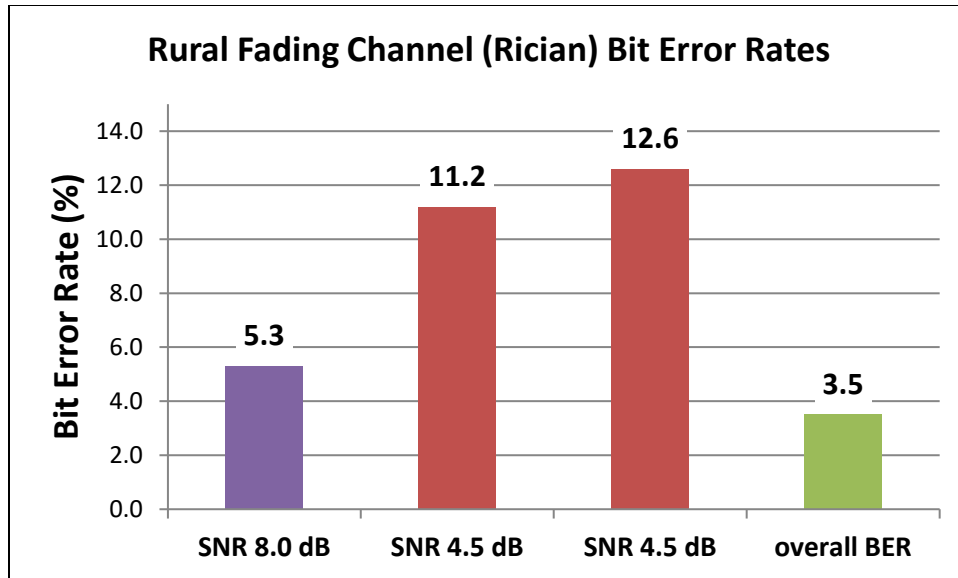


(a) 3 relays

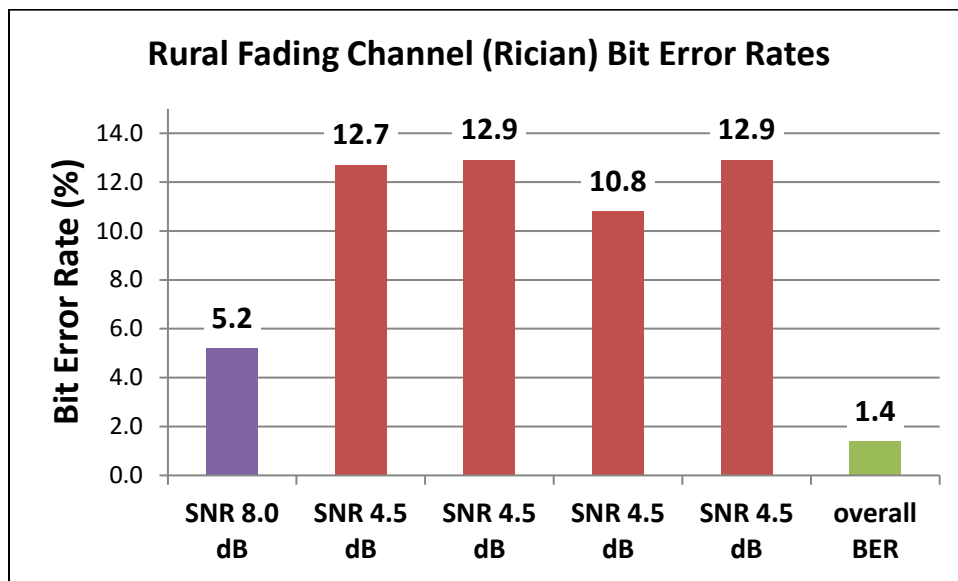


(b) 5 relays

Figure 24 – Rural channel, 3 relays (medium, medium, far) vs. 5 relays (medium, medium, far, far, far)

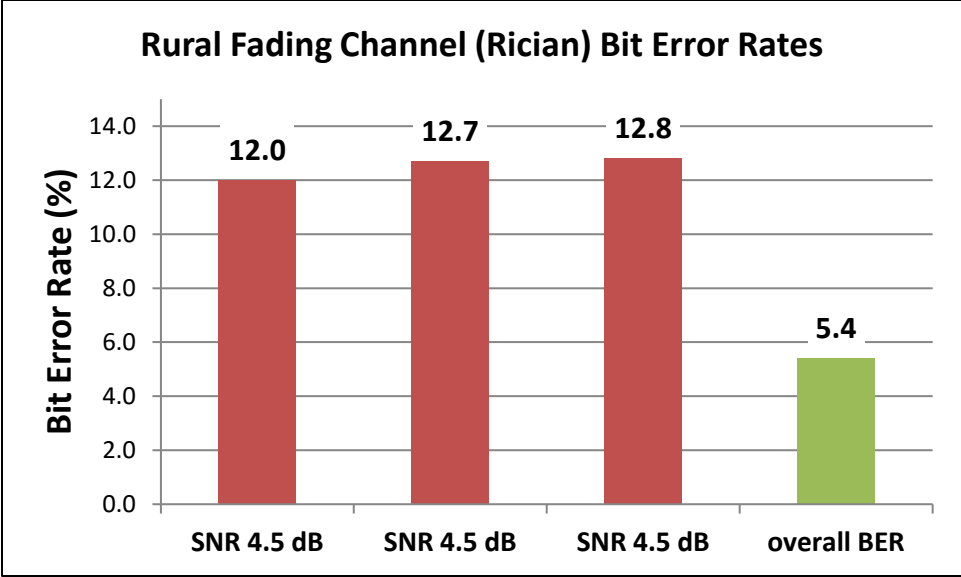


(a) 3 relays

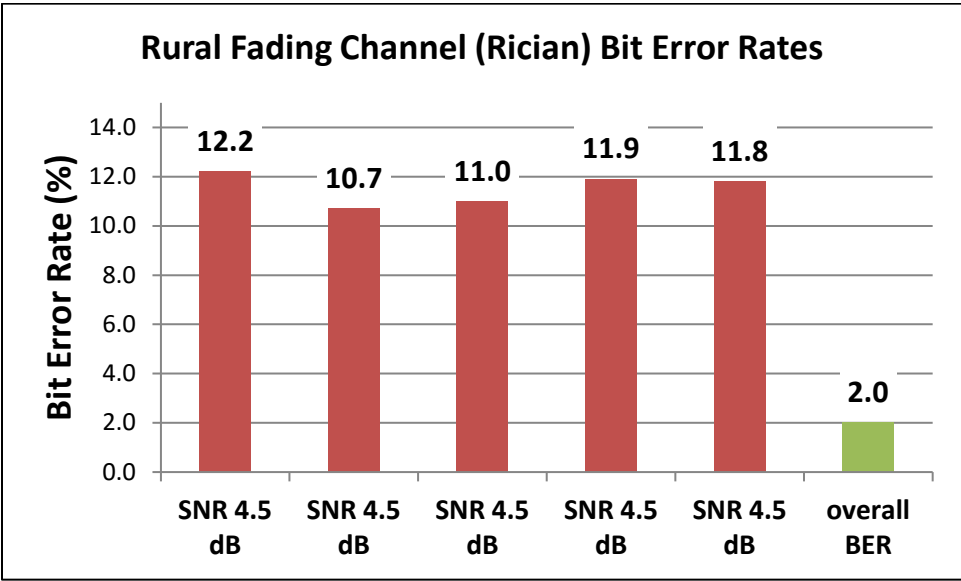


(b) 5 relays

Figure 25 – Rural channel, 3 relays (medium, far, far) vs. 5 relays (medium, far, far, far, far)



(a) 3 relays



(b) 5 relays

Figure 26 – Rural channel, 3 relays (far, far, far) vs. 5 relays (far, far, far, far, far)