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IMPROVING THE RELIABILITY OF IN VIVO VIDEO WIRELESS COMMUNICATIONS

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The *MARVEL* wireless research platform for advancing minimally invasive surgery requires high bit rates (~100 Mbps) for high-definition transmission. Orthogonal frequency division multiplexing (OFDM) is a widely used technology in fourth-generation wireless networks (4G) that achieves high transmission rates over dispersive channels by transmitting serial information through multiple parallel carriers. Combining *diversity coding* with OFDM (DC-OFDM) promises high-reliability communications while preserving high transmission rates. Most of the OFDM subchannels transport original information while the remaining (few) carriers transport diversity coded (protection) information. Implementing diversity coding in OFDM-based systems provides reliable communication that is quite tolerant of link failures, since the data and protection lines are transmitted via multiple subchannels. Moreover, only adding one protection line (subcarrier), DC-OFDM provides significant performance improvement. The impact of DC-OFDM can extend far beyond in vivo video medical devices and other special purpose wireless systems and may find significant application in a broad range of ex vivo OFDM-based wireless systems, such as LTE, 802.11, and 802.16.

Key words: In vivo communications; Diversity coding (DC); Orthogonal frequency division multiplexing (OFDM)

INTRODUCTION

While there has been significant recent work on the potential performance of wireless body area networks (WBANs) by the IEEE P802.15 TG6 WBAN channel model (10), there is far less research on communicating information across the boundary of the body (i.e., between in vivo and on-body or other external devices). Naturally, such communication poses significant difficulties. First, for radio frequency (RF) communication, the body is relatively lossy, making the establishment of links with high signal-to-noise ratio (SNR) and therefore high data rates challenging. Also, because the dielectric parameters of internal tissues depend on the operating frequency and a typical end-to-end propagation path consists of multiple components associated with many types of tissues, it can be difficult to couple electromagnetic fields efficiently into or out of the body.

There are key technical challenges to the efficient use of the in vivo RF spectrum for access to embedded medical devices, especially for real-time traffic such as video streaming applications, which require high transmission data rates. Our target application is the MARVEL camera module (2,7), which transmits real-time video from the abdominal cavity. For this application, we need to provide high data transmission rate while maintaining adequate reliability levels. This is why we explore orthogonal frequency division multiplexing (OFDM) to realize high data rates and apply diversity coding across subcarriers. Diversity coding can improve the reliability of the OFDM-based communication because retransmissions are not a good alternative for this real-time traffic application.

In this article, using diversity coding, we intend to enhance the performance and increase the reliability

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of these point-to-point OFDM wireless connections by transmitting data in some set of subcarriers and protection data (redundant information) through another subset of carriers. Figure 1 shows an overview of the implementation of diversity coding in OFDM-based systems.

The rest of the article is organized as follows. In the second section we give an overview about OFDM. In the third section we describe diversity coding (DC), a technique to increase the communication performance. Our approach, DC-OFDM, is presented in the fourth section and the fifth section presents results of the performance of DC-OFDM. Finally, in the last section we present our conclusions and future research directions.

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM (11) is a widely used technology in fourth-generation wireless network (4G) that achieves high transmission rates over dispersive channels by transmitting serial information through multiple parallel carriers. The transmission bandwidth is divided into many narrow subchannels, which are transmitted in parallel, such that the fading each channel experiences is flat.

Instead of modulating a digital information stream on one carrier waveform (as in QAM), in OFDM the information stream is broken into many lower data rate streams that are transmitted in parallel. The parallel data transmission scheme in OFDM reduces the effect of multipath fading and makes the use of complex equalizers unnecessary. OFDM is derived from the fact that the digital data are sent through many subcarriers, each of a different frequency, and these subcarriers overlap but are orthogonal to each other, and hence OFDM is an effective technique to transmit wideband signals. $M-QAM$ and $M-PSK$ signals, where M is the modulation order, may be used within each subchannel to realize data rate appropriate for that subchannel.

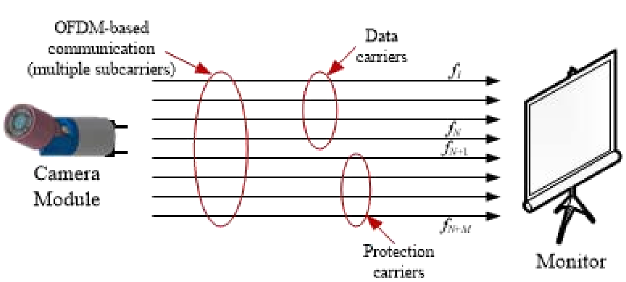

Figure 1. Overview of DC-OFDM.

Figure 2 shows a comparison in time and frequency domain between single carrier and OFDM systems. As we can see there, when there are multipath fading effects, OFDM provides enhanced performance compared to single carrier systems for wideband transmissions because each subcarrier in OFDM experiences flat fading.

The OFDM signal can be expressed as

$$s(t)=\sum_{k=0}^{N-1} X_k e^{\frac{j2\pi kt}{T}}, t\equiv[0,T) \tag{1}$$

where $\{X_k\}$ are the data symbols, N is the number of subcarriers, and T is the OFDM symbol duration. The orthogonality condition is given by

$$\int_0^T e^{\frac{j2\pi k_1 t}{T}} e^{\frac{j2\pi k_2 t}{T}} dt=\delta_{k1k2} \tag{2}$$

where $\delta_{k_1k_2}$ is the Kronecker delta function. This function has the following values:

$$\delta_{k_1k_2}=\begin{cases}1, & if\ k_1=k_2\\ 0, & o.w.\end{cases} \tag{3}$$

The probability of symbol error for a QPSK modulated OFDM signal under an AWGN channel is given by (9);

$$p_s(\gamma)=2Q\left(\sqrt{2\gamma}\right)-Q^2\left(\sqrt{2\gamma}\right) \tag{4}$$

If we consider a Rayleigh distributed channel, (4) becomes (9)

$$p_s(\overline{\gamma})=\frac{3}{4}-\sqrt{\frac{\overline{\gamma}}{1+\gamma}}\left(1-\frac{1}{\pi}\tan^{-1}\sqrt{\frac{\overline{\gamma}}{1+\gamma}}\right) \tag{5}$$

where

$$\overline{\gamma}=\frac{E_b}{\left(\frac{\pi fd}{\Delta f}\right)^2\frac{E_b}{3}+N_0} \tag{6}$$

$$f_d=\frac{vf_c}{c} \tag{7}$$

$$\Delta f=\frac{1}{T} \tag{8}$$

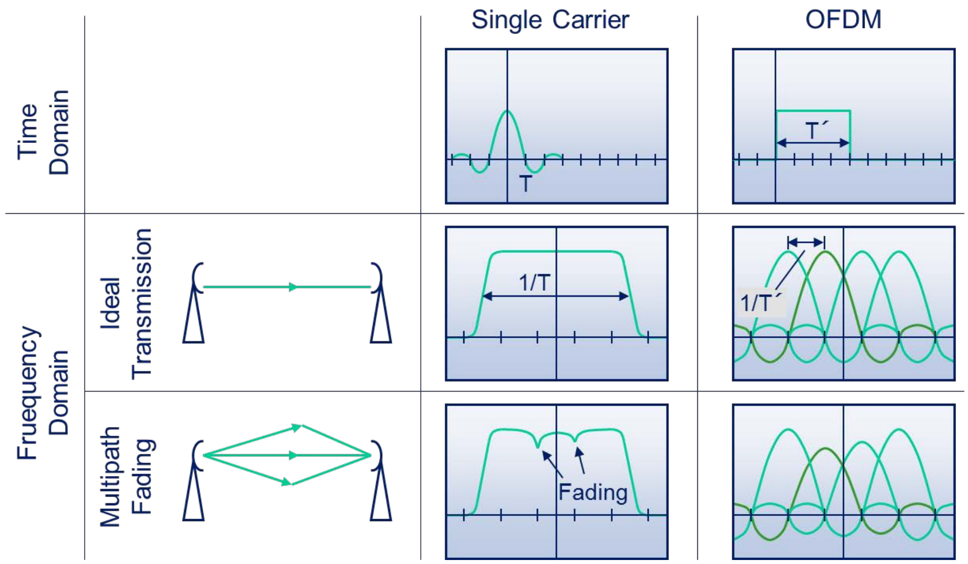

Figure 2. Comparison between single carrier transmission and OFDM.

where f_d is the maximum Doppler shift, v is the relative speed between the transmitter and receiver, f_c is the carrier frequency, and c is the speed of light. The total bandwidth is calculated as the product between the number of subcarriers (N) and the subcarrier spacing (Δf).

Assuming that all subcarriers experience independent channel conditions and that the probability of symbol error is the same for all subcarriers, the probability of having η symbol errors in an OFDM symbol is calculated by the probability mass function of the binomial distribution,

$$P(\eta) = \binom{N}{\eta}(1 - p_s(\bar{\gamma}))^{N-\eta}(p_s(\bar{\gamma}))^{\eta} \qquad (9)$$

The probability of having no symbol errors in an OFDM symbol can be calculated as

$$P(\eta = 0) = (1 - p_s(\bar{\gamma}))^{N} \qquad (10)$$

DIVERSITY CODING

Diversity coding (DC) (5,6,8) is a feed-forward spatial diversity technology that enables near instant self-healing and fault tolerance in the presence of wireless link failures. The protection paths (c_i) carry information that is the combination of the uncoded data lines (d_i). Figure 3 shows a diversity coding system that uses a spatial parity check code for a point-to-point system with N data lines and 1 protection line. If any of the data lines fail (e.g., d_3), through the protection line (c_i), the destination (receiver) can recover the information of the data line that was lost (d_3) by taking the mod 2 sum of all of the received signals. This model can be generalized to an M-for-N diversity coding system as shown in (5).

A network is transparently self-healed when any combination of N links survive among M diverse links. This technique is very efficient without the necessity of having the packets reroute in other directions.

Assuming there are N links in the network, d_j to be the information carrying bits in the binary form, and there is an extra line present to protect the network from fading or other failures.

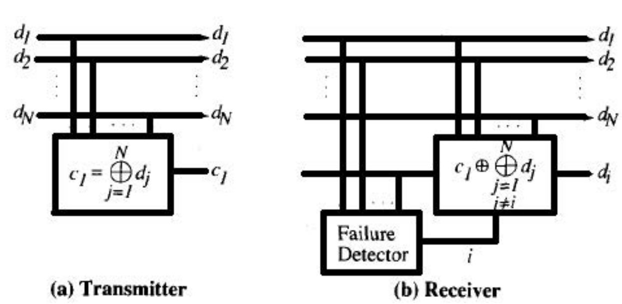

Figure 3. 1-for-N DC system (5).

$$c_1 = d_1 \oplus d_2 \oplus \ldots \oplus d_N \tag{11}$$

$$c_1 = \oplus_{j=1}^{N} d_j \tag{12}$$

where $\oplus$ represents the XOR function and the extra line $N+1$ carries the checksum c_1. If any one of the lines between 1 and N fails, then the receiver detects the line/channel with failure and obtains $\hat{d}_i$:

$$\hat{d}_i = c_i \oplus \oplus_{\substack{j=1 \\ j \neq i}}^{N} d_j \tag{13}$$

According to Equation 13, the estimated unknown variable $\hat{d}_i$ can be calculated from the logical XOR function performed on all the d_j variables from 1 to N, except d_i. After expanding c_1 (12), it is easy to obtain the information of the failed i^{th} line as $d_j \oplus d_j = 0$ and $d_i = d_i$.

$$\hat{d}_i = \oplus_{j=1}^{N} d_j \oplus \oplus_{\substack{j=1 \\ j \neq i}}^{N} d_j \tag{14}$$

Expanding Equation 14, we have;

$$\hat{d}_i = (d_1 \oplus \ldots \oplus d_i \oplus \ldots \oplus d_N) \oplus (d_1 \oplus \ldots \oplus d_{i-1} \oplus d_{i+1} \ldots \oplus d_N) \tag{15}$$

Given that $d_j \oplus d_j = 0$, Equation 15 becomes:

$$\hat{d}_i = d_i \tag{16}$$

By using just one extra line, the lost information in the failed link can be recovered instantaneously without rerouting or providing a feedback channel to the transmitter.

Assuming that the probability of link error (p_i) is the same for all the links ($p = p_i$, $\forall i$), the probability of successfully receive the correct information through at least any x links, out of the N data lines plus 1 protection line ($N+1$), is calculated as:

$$Ps = Prob(x) \tag{17}$$

$$P_s = \sum_{t=1}^{N-1} \left(\left(\frac{\prod_{i=1}^{t} i}{(N+1)^t} \right) \binom{N+1}{t} (1-p)^t (p)^{N+1-t} \right) + \sum_{t=N}^{N+1} \left(\binom{N+1}{t} (1-p)^t (p)^{N+1-t} \right) \tag{18}$$

Rewriting Equation 18, we have that the probability of successful reception at the destination is calculated as:

$$P_s = \sum_{t=1}^{N-1} \left(\left(\frac{\prod_{i=N+2-t}^{N} i}{(N+1)^{t-1}} \right) (1-p)^t (p)^{N+1-t} \right) + \sum_{t=N}^{N+1} \left(\binom{N+1}{t} (1-p)^t (p)^{N+1-t} \right) \tag{19}$$

However, since the region of interest is when the information has been correctly received through at least N links, Equation 19 is reduced to:

$$P_s = \sum_{t=N}^{N+1} \left(\binom{N+1}{t} (1-p)^t (p)^{N+1-t} \right) \tag{20}$$

Because the first term of P_s is the probability of correctly received the information of at least one link and at most $N-1$ links is zero. That is,

$$\sum_{t=N}^{N-1} \left(\left(\frac{\prod_{i=N+2-t}^{N} i}{(N+1)^{t-1}} \right) (1-p)^t (p)^{N+1-t} \right) = 0 \tag{21}$$

As shown in Figure 3 and Equation 12, each link can carry as few as one bit to implement a 1-for-N diversity coding system because with one bit we can calculate Galois Field of up to two elements $\{0,1\}$, $GF(2^1)$. In other words, the number of bits per link limits the number of protection links. That is, the larger the number of bits to be transmitted by each link, the larger the number of protection links that can be implemented. This is because the number of protection links is limited to the Galois field [$GF(2^q)$] size q to calculate the information that is transmitted through the protection links.

This concept can be extended to multiple line failures and also to recover lost packets in packet-based networks. The delay in a network changes whenever there is a link failure and when recovery is needed; otherwise, the delay in a normal operating network is constant. The delay occurs because the system contains different links, each having different lengths, with each link causing delay based on the distance between source node and destination node.

For an M-for-N diversity coding system, the coded information is calculated as (5)

$$c_i = \sum_{j=1}^{N} \beta_{ij} d_j \quad i \in \{1, 2, \ldots, M\} \tag{22}$$

where c_i and d_j are protection (diversity coded) and data (uncoded) packets, respectively. The β coefficients are given by

$$\beta_{ij} = \alpha^{(i-1)(j-1)} \tag{23}$$

where α is a primitive element of a Galois field $GF(2^q)$, $i=\{1,2,\ldots,M\}$ and $j=\{1,2,\ldots,N\}$.

The total number of transmitted packets is equal to the number of data packets plus the number of protection packets ($N+M$), where the number of protection packets is typically less than the number of data packets ($M \leq N$). We define the DC code rate as the number of data lines (subcarriers) to the number of data plus protection lines (subcarriers) ratio:

$$\text{DC code rate} = \frac{N}{N+M} \tag{24}$$

We can calculate the number of protection lines as a function of the data lines and DC code rates as

$$M = \frac{(1-\text{DC code rate})N}{\text{DC code rate}} \tag{25}$$

At the receiver, the coefficients of the data and protection lines form the following matrix, which depends on the information that was correctly received at the destination:

$$\beta' = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ 1 & \alpha & \alpha^2 & \ldots & \alpha^N \\ 1 & \alpha^2 & \alpha^4 & \cdots & \alpha^{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha^{(M-1)} & a^{(M-1)2} & \cdots & a^{(M-1)N} \end{bmatrix} \tag{26}$$

The receiver, by using the β' matrix coefficients, an ($N+M$)–-by -N matrix, can find the transmitted data by recovering the lost information in the data lines through the protection lines. That is, the receiver uses only N rows out of the $N+M$ rows from the β'_N matrix coefficients to recover the information of the data lines,

$$\beta'_N x = b_N \tag{27}$$

The receiver preferably uses as many indexes of the data lines as possible to faster decode the information that is lost during transmission. If no data line is lost during transmission, no decoding process is needed at the receiver and the information transmitted through the protection lines is discarded. x is the vector formed by the data lines,

$$x = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} \tag{28}$$

and b_N is the vector formed by the correctly received information at the destination with the same indexes as the β'_N matrix.

The receiver can recover the lost information transmitted through the data lines by performing Gaussian elimination to the β coefficients (protection lines). This is a fast process because some of the row elements of the coefficients matrix are already in the row canonical form.

Assuming that the probability of link error (p_i) is the same for all the links ($p=p_i,\ \forall i$), the probability of successfully receiving the correct information through at least any N links, out of the N data lines plus M protection lines, is calculated as:

$$P_s = Prob(x \geq N) \tag{29}$$

$$P_s = \sum\nolimits_{t=N}^{N+M} \left(\binom{N+M}{t} (1-p)^t (p)^{N+M-t} \right) \tag{30}$$

However, the assumption that all the links have the same probability of link error may be unrealistic because each link can experience different channel effects. A general formula to calculate the probability of successfully receiving the correct information through at least any N links out of the N data lines plus M protection lines is

$$P_s = Prob(x \geq N) \tag{31}$$

$$P_s = \sum\nolimits_{t=N}^{N+M} \left[\sum\nolimits_{\vec{\alpha}\in A} \left(\prod\nolimits_{i\in\alpha_2} \cdot \prod\nolimits_{i\in\alpha_0} p_i (1-p_j) \right) \right] \tag{32}$$

where

A is a set of $N+M$ binary sequences of all the 2^{N+M} possible combinations. A binary sequence can contain either 0 or 1, where "1" means that the transmission was successful and "0" otherwise. The number of 1-s in A is t and the number of 0-s is $(N+M-t)$; so there are $\binom{N+M}{t}$ such sequences. Thus,

$$\|A\| = \binom{N+M}{t} \tag{33}$$

$\vec{\alpha}$ is a particular sequence from the set A, α_0 is a set of all indices j of $\vec{\alpha}$ such that $\alpha(j)=0$, and α_1 is a set of all indices i of $\vec{\alpha}$ such that $\alpha(j)=1$. Thus,

$$\|\alpha_0\| + \|\alpha_1\| = N+M \tag{34}$$

p_i is the probability that the information transmitted through subcarrier i is correctly received at the destination.

The expected number of correctly received information packets ($\mathbb{E}$) can be calculated as in Network Coding as:

$$\mathbb{E} = N * Ps \tag{35}$$

Diversity coding can be applied to different network topologies, where the topology is known. For example, Figures 4–6 show different network topologies for DC, where c denotes the vector of diversity coded bits.

In multipoint-to-multipoint diversity coding, the protection paths from each source form a vector that carries the protection information of all the sources. At the destinations, a central decoder receives input (data lines) from the destination nodes. Based on the input from the receivers and with the aid of the parity (protection) vector, the data that were lost during the transmission can be recovered.

There has been considerable research on network coding (NC) (1), which is related to diversity coding, to improve the performance of different type of networks. These approaches are applied at packet, symbol, or signal levels.

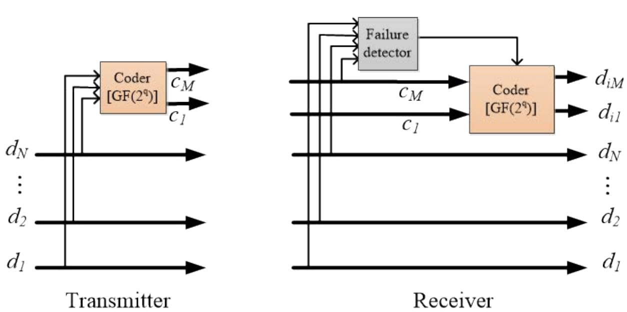

Figure 4. Point-to-point system with M-for-N DC (5).

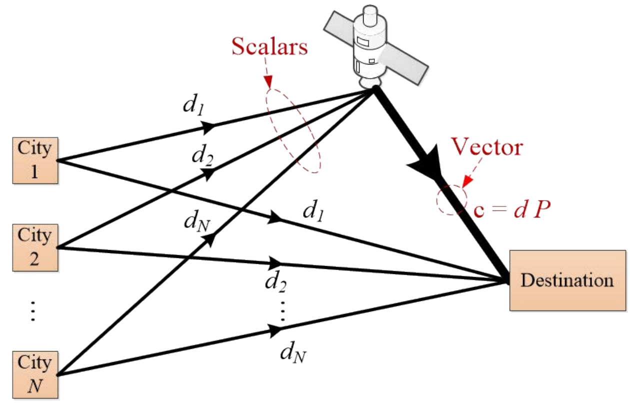

Figure 5. Multipoint-to-point DC (5).

DIVERSITY CODING–ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

Combining diversity coding with orthogonal frequency division multiplexing (DC-OFDM) promises high reliability communications while preserving high transmission rates. This is achieved by transmitting coded information across the OFDM carriers (spatial protection). That is, most of the carriers transport original information while the remaining (few) carriers transport coded information. The coded information is the result of the combination of the original information as in diversity coding. As shown in Figure 7, if any of the carriers that transport data (d_0, d_1, up to d_{N-2}) is lost because of a fade or because of the number of errors in a carrier is bigger than the error correction capability of the forward error correction code (FEC), the information from the lost carrier can be recovered from the (received) protection carriers (d_{N-1} for this simple example). That is, if any carrier that has data is in a fade, the information of that OFDM carrier can be recovered from the protection data received through other carriers. This novel technique of applying coding across carriers differs from the traditional coded OFDM where channel coding techniques, such as convolutional codes, Reed-Solomon codes, are used to combat noise floor.

The protection information (c_i) that is transmitted through the protection carriers is calculated as (22)

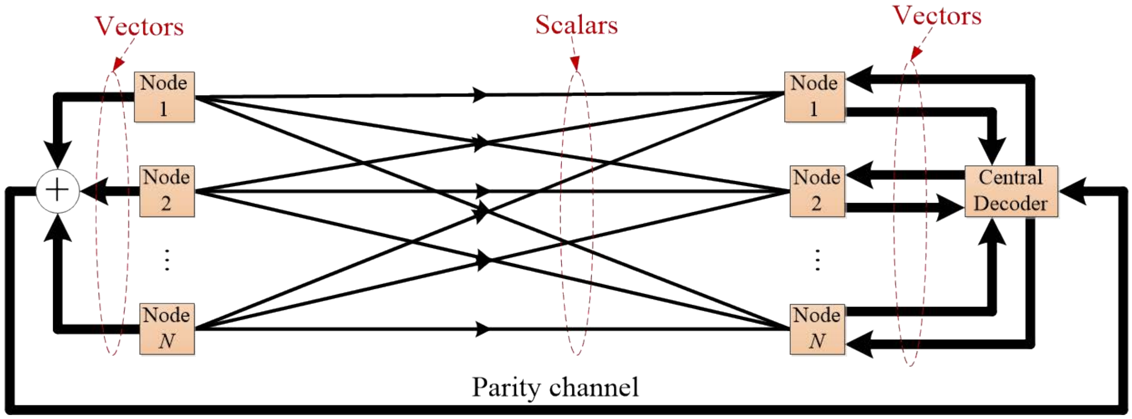

Figure 6. Multipoint-to-multipoint DC (5).

$$c_i = \sum_{j=1}^{N} \beta_{ij} d_j \quad i \in \{1,2,\ldots,M\} \tag{36}$$

where d_j is data (uncoded) information. The β coefficients are given by

$$\beta_{ij} = \alpha^{(i-1)(j-1)} \tag{37}$$

where α is a primitive element of a Galois field $GF(2^q)$, $i = \{1,2,\ldots,M\}$ and $j = \{1,2,\ldots,N\}$.

The total number of data plus protection lines (subcarriers) should be at most equal to the FFT size because the number of subcarriers is limited to the FFT size,

$$N + M \leq FFT_{size} \tag{38}$$

The probability of successfully receiving the correct information through at least any N links out of the N data lines plus M protection lines can be calculated as (3)

$$P_s = Prob(x \geq N) \tag{39}$$

$$P_s = \sum_{t=N}^{N+M} \left[\sum_{\vec{\alpha} \in A} \left(\prod_{i \in \alpha_1} \cdot \prod_{j \in \alpha_0} p_i (1 - p_j) \right) \right] \tag{40}$$

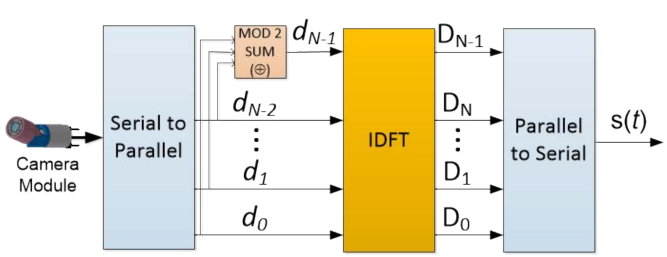

Figure 7. System with 1-for-N DC-OFDM in vivo communication links.

where

A is a set of $N+M$ binary sequences of all the 2^{N+M} possible combinations. A binary sequence can contain either 0 or 1, where "1" means that the transmission was successful and "0" otherwise. The number of 1-s in A is t and the number of 0-s is $(N+M-t)$; so there are $\binom{N+M}{t}$ such sequences. Thus,

$$\|A\| = \binom{N+M}{t} \tag{41}$$

$\vec{\alpha}$ is a particular sequence from the set A, α_0 is a set of all indices j of $\vec{\alpha}$ such that $\alpha(j) = 0$, and α_1 is a set of all indices i of $\vec{\alpha}$ such that $\alpha(j) = 1$. Thus,

$$\|\alpha_0\| + \|\alpha_1\| = N + M \tag{42}$$

p_i is the probability that the information transmitted through subcarrier i is correctly received at the destination.

Equation 40 can be reduced to the cumulative distribution function of a binomial distribution when the probability of link error (p_i) for each subcarrier is the same for all the links (subcarriers) ($p = p_i$, $\forall i$). Therefore, the probability of successfully receiving the correct information through at least any N links, out of the N data lines plus M protection lines, is calculated as

$$P_s = Prob(x \geq N) \tag{43}$$

$$P_s = \sum_{t=N}^{N+M} \left(\binom{N+M}{t} (1-p)^t (p)^{N+M-t} \right) \tag{44}$$

Note that the probability of link error is equal to the probability of symbol error.

Table 1. Diversity Coding as a Function of the Modulation Scheme

Modulation	Coded Bits per Subcarrier (N_{BPSC})	Max Rank GF(2bits)
BPSK	1	1
QPSK	2	3
16 QAM	4	15
64 QAM	6	24

If we apply diversity coding based on the modulation scheme (assuming that all subcarriers use the same modulation scheme), the maximum number of protection subcarriers that can be created depends on the number of bits used by each modulation. Table 1 shows the maximum number of protection subcarriers that can be created.

We are implementing this technique on a FPGA-based development kits to test its performance. The implementation structure is shown in Figure 8.

In the following section, we present results that compare the performance between OFDM systems that do not use diversity coding and systems that use diversity coding.

PRELIMINARY RESULTS

In this section, we show the results of the performance of diversity coding on OFDM-based systems. We have studied several scenarios such as the effect of the number of data carrier, the number of protection carriers, and the probability of link error (probability of symbol error).

The performance of an M-for-N DC-OFDM system as a function of the number of data carriers for an OFDM-QPSK modulated system is shown in

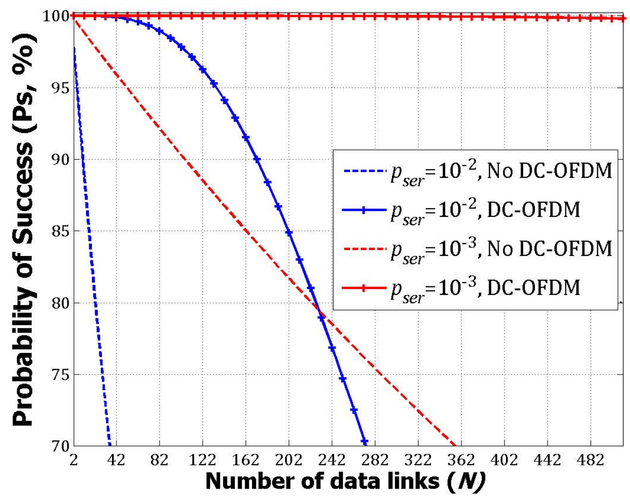

Figure 9. Performance of 3-for-N DC-OFDM system for an OFDM-QPSK.

Figure 9. As we can see, DC-OFDM provides significant performance improvement for OFDM-based communications. The results shown below are for an OFDM-QPSK system that uses the maximum number of protection links that can be implemented with a QPSK modulation. In other words, it uses three protection carriers (3-for-N DC-OFDM).

Figure 10 shows the performance of DC-OFDM as a function of the number of data link for different number of protection links. We can see in Figure 10 that, for a probability of symbol error of 10^{-2} and 48 data links, 3-for-N DC-OFDM provides a performance improvement of about 40% compared to an OFDM system that does not uses diversity coding. Moreover, by only using one protection link in a 48 data link OFDM system, a performance improvement of about 30% can be achieved.

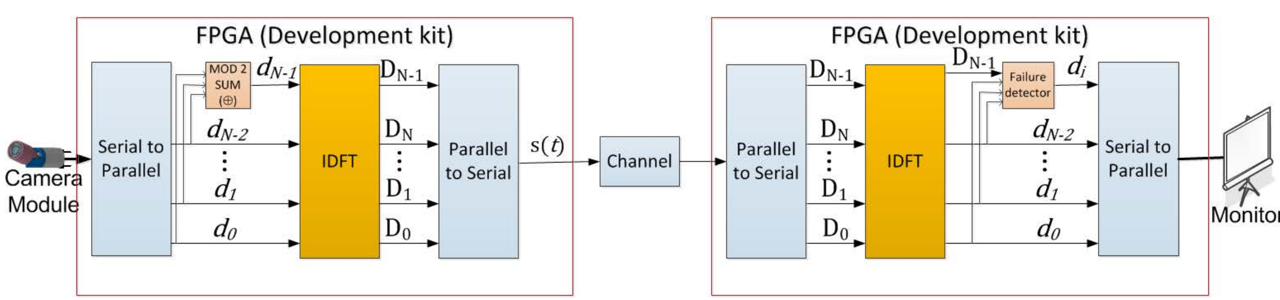

Figure 8. Schematic to implement DC-OFDM in vivo communication links.

The probability of successful reception for *M*-for-*N* DC-OFDM system versus the energy per bit to noise power spectral density ratio (E_b/N_0) for an OFDM-QPSK modulated system is shown in Figure 11. As we can see, 3-for-*N* DC-OFDM achieves full throughput when the energy per bit is about 16 dB (E_b/N_0=16 dB), while OFDM without diversity coding requires about 35 dB to achieve the same performance.

CONCLUSIONS

Diversity Coding–OFDM (DC-OFDM) maximizes the probability of successful reception and increases the reliability of OFDM-based systems. DC-OFDM is a promising technology to improve the reliability and performance of real-time in vivo video transmission where high data rates and reliability are required. Moreover, DC-OFDM significantly improves the performance of OFDM-based networks in terms of maximizing the expected number of correctly received symbols.

For example, 3-for-*N* DC-OFDM achieves up to a 40% performance gain in the probability of successful reception, when compared to systems that do not use DC-OFDM for an OFDM-QPSK modulated system with a probability of link error (probability of symbol error) of 10^{-2}. From another viewpoint, 3-for-*N* DC-OFDM requires up to 19 dB less energy per bit to achieve the same performance as a system that does not use DC-OFDM.

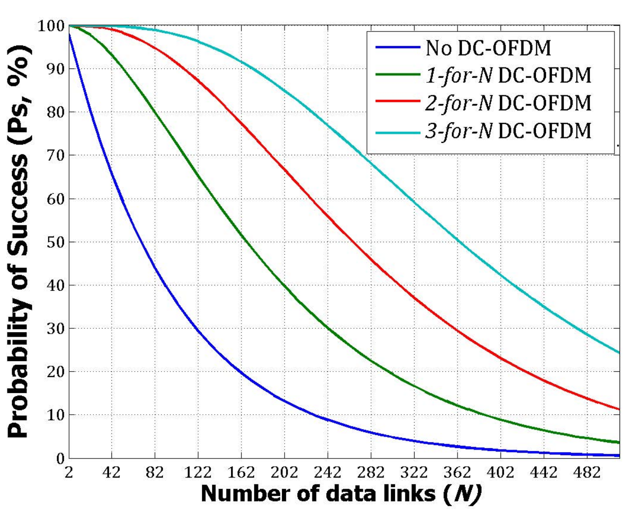

Figure 10. Performance of *M*-for-*N* DC-OFDM system for an OFDM-QPSK with probability of link error equal to 10^{-2}.

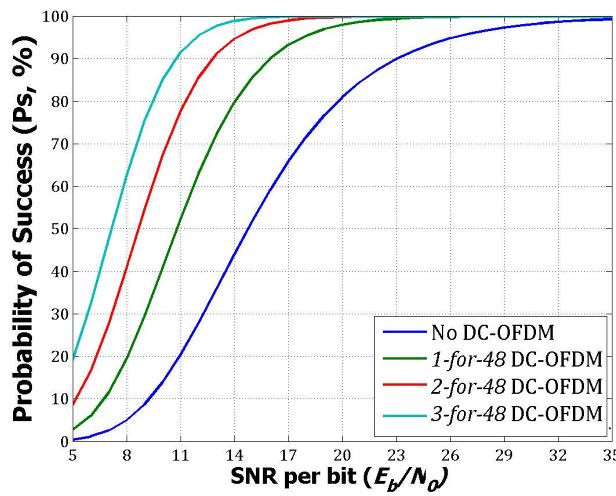

Figure 11. Performance of *M*-for-*N* DC-OFDM system for an OFDM-QPSK as a function of the E_b/N_0.

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