A Novel Superposition Multi Rate Coded Modulation (SMRCM)

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Abstract—This paper is concerned with the design of a wireless data transmission which provides Un-equal Error Protection (UEP). A novel Superposition Multi Rate Coded Modulation (SMRCM) system has been introduced. In the proposed SMRCM, the user data bit stream can be divided into two bit streams. The first bit stream represents the region of High Priority (HP), while the second represents the region of Low Priority (LP). These two bit streams are encoded, spread and interleaved separately. The resultant chip interleaved sequences are modulated and superimposed together to achieve UEP at the receiver side. A simple Chip-By-Chip (CBC) iterative Multi User Detection (MUD) strategy is used. In AWGN channel, the proposed SMRCM performance is better than Un-coded Superposition Modulation (USM) and Un-equal Error Protection Superposition Coded Modulation (UEP-SCM) by $0.3 \, \text{dB}$ respectively, but degraded by $0.3 \, \text{dB}$ compared with Equal Error Protection Superposition Coded Modulation (EEP-SCM) at $\text{BER} = 10^{-4}$. The performance is investigated over AWGN and Rayleigh fading channels in the presence of High Power Amplifier (HPA).

Keywords- SCM; UEP; HPA; CBC Iterative decoding.

I. INTRODUCTION

Any communication channel is characterized by a so-called channel capacity. Operating near capacity implies power efficiency and simultaneously bandwidth efficiency. Obviously, there is a trade-off between power and bandwidth efficiency. Therefore, achieving power and bandwidth efficiency simultaneously is a challenging task [1], as well as, in future Broadband Wireless Access (BWA) systems; the main challenge is to transmit an error sensitive application data with a higher bit rate efficiently over error prone wireless channels. Error performance of communication channels is usually poor without error control due to channel imperfections and the inherent additive noise.

Using error control coding will cause bandwidth expansion, which is not desirable, where; the limitation and higher cost of spectrum occupation are among the most important challenges in wireless communication systems. In order to overcome this drawback, such coding and modulation should be integrated to match the channel situation, Coded Modulation (CM) schemes are used to achieve both power and bandwidth efficient communication by mapping information sequences onto an expanded set of channel signals with the help of error correcting codes [1-3].

In such EEP systems, a fixed code is constructed for the worst case of average channel/source conditions, this result in the waste of resource for the protection of the least sensitive bits, since they are assigned the same protection level as the most sensitive bits. A classic technique that used for maximizing error control performance while limiting the required redundancy is to apply UEP [4]. Codes that are designed to provide different levels of data protection are known as UEP codes, the term UEP implies that the resources available to provide protection to the various bit streams are not equally distributed, but instead, each bit stream may be protected so that it withstands a different level of channel noise.

Simply, different levels of protection are provided for different parts of the data according to their degrees of importance, UEP receiver matches the protection level according to the system requirement, and thus can save the system resources. For example, in packet communications, the header must be protected more than the payload, because in the worst case, if the destination address is lost, the entire packet will be lost.

A multilevel encoder in [5] is considered an UEP system, the information sequence is divided into parallel sequences in decreasing order of importance, and the encoding process consists of the different rate encoders to create the desired UEP characteristics. Specific examples include practically all digital speech and image transmission systems. SCM is considered one of the design methods for UEP which implies transmission of different symbol streams on the same modulation interval, it is a powerful modulation technique that is being considered in many emerging broadband communication systems.

SCM has been studied as an alternative scheme for high throughput transmission [6-7]; it has several advantages over conventional CM schemes. One interesting feature of SCM is that, the transmitted signal exhibits an approximately Gaussian distribution since it is a linear superposition of several independent code words (each referred to as a layer). Superposition coding is conceptually simpler and has lower encoding complexity.

Another feature of superposition coding is that it can be treated as a perfectly cooperating multiple access system by
viewing one layer as one user. Hence, the low cost CBC iterative decoding techniques developed in [8] can be employed.

The most common types of power amplifiers used in communication systems are Travelling Wave Tubes Amplifiers (TWTA) and Solid State Power Amplifiers (SSPA). Obviously HPAs are a part of almost all communication links and due to the non-linear nature of the electronic components that they are made of, their conversion characteristics are non-linear.

In general, two major classes defining the time behavior of HPA; HPA models with memory and memory-less HPA models. The word memory-less implies not only an instantaneous relationship between input and output, but also implies that the device does not exhibit frequency selective behavior over the bandwidth of operation. In addition to amplify the signal, the non-linear amplifier generates non-linear distortion in both amplitude and phase which causes the loss of system reliability resulting in a higher BER [9, 10].

In this paper, a single user 2-layer SMRCM system is introduced, the coding scheme is designed in such a way that the most important information bits result in a better error rate than other information bits using different rate convolutional encoders. All of the layers employ a common spreading sequence, the interleaving index sequences is considered as a code to distinguish layers. Synchronous Binary Phase Shift Keying (BPSK) signaling is considered over a time-invariant single path channel with equal power allocation in the presence of non-linear HPA Rapp model, considering both AWGN and Rayleigh fading channels. A simple CBC iterative MUD strategy is applied.

This paper is organized as follows, a transmitter structure for the proposed SMRCM in the presence of non-linear HPA is presented in section II, section III, introduces a CBC iterative MUD, the proposed SMRCM system performance evaluation compared with USM, SCM-Uep and SCM-Eep in section IV, the conclusions are presented in Section V.

II. SMRCM TRANSMITTER STRUCTURE

A. Encoding

SCM has been investigated by many authors [1-3], [11, 12]. SCM consists of transmitting both streams in all available modulation intervals using superposition of channel codes in the modulation space. The transmitter of the proposed system is depicted in Fig. 1. For simplicity, synchronous BPSK signaling is considered over a time invariant single path channel.

A single user binary data sequence, \( \mathbf{x} \in \{+1,-1\} \), is unequally partitioned based on data priority into \( k \) subsequences \( \{d=d_1,\ldots,d_k, k = 1,2,\ldots,K\} \), the \( k^{th} \) subsequence is encoded using different rate convolutional encoders at the \( k^{th} \) level, resulting in coded sub-sequences, \( \{c_1,\ldots,c_k\} \), spread using a length \( S \) spreading sequences \( S^k \in \{+1,-1\} \), the same composite spreading sequence is applied to all layers. The encoded chip sequence obtained after spreading is written as, \( \{S^j\}_j \), where, \( j = S \times N \) is the frame length. In contrast to Code Division Multiple Access (CDMA), specific spreading codes are used for layers separation. Interleaving is essential for system performance, as it reduces the mutual dependence among superimposed chips.

A specific distinct chip layered random interleavers are employed as layer specific interleavers for layer separation, \( \{\pi_j, k = 1,2,\ldots,K\} \), to produce interleaved chip layered data sequences, \( \{I_j\}_j \), the interleaved chips layered data sequences are mapped onto the modulated symbols, \( \{x_j, \ldots, y_j\} \), which are elements of a BPSK constellation. Afterward, the modulated symbols are weighted, this weighting corresponds to power and phase allocation and is crucial for the performance of SM, to simplify discussion, the weighting factor \( \beta^k \) is assumed to be real constant weighting factor, i.e., the magnitudes of chips are all identical and set to 1, the weighted symbols are superimposed together to produce the SMRCM signal sequence \( \mathbf{r}_j \).

![Figure 1. Transmitter structures of the proposed SMRCM](image)

\( \mathbf{r}_j = \sum_{k=1}^{K} \beta^k x_j^k \quad (1) \)

\( \mathbf{r}_j \), is fed to the HPA, non-linearly amplified, as given in [9]. Rapp model is used for modeling memory-less SSPA behavior models for the proposed SMRCM system, the output of HPA, \( \mathbf{x}_j \), is given by:

\( x_j(t) = A(t)\cos\left[\omega c t + \phi(t)\right] \quad (2) \)

Where, \( F[A(t)] \) and \( \Psi[A(t)] \) are the gain distortion function that represents the Amplitude to Amplitude transfer characteristics \( \frac{AM}{AM} \), and the phase distortion function that represents Amplitude to Phase transfer characteristics \( \frac{AM}{AP} \), of the SSPA non-linearity Rapp model respectively, which are given by:

\[
\begin{align*}
F[A(t)] &= A(t) - A(t)^2 \frac{AM}{AM} \\
\Psi[A(t)] &= \frac{AM}{AP} + \frac{AM}{AP} A(t) - \frac{AM}{AP} A(t)^2
\end{align*}
\]
\[ A_{M/AM} : F[x_j] = x_j = \frac{x_j}{\left(1 + \frac{x_j}{v_{sat}}\right)^{2p}} \]

\[ A_{M/PM} : \Psi(A(t)) = 0 \]

\( x_j, x_n \) are the input and output signals voltage, \( v_{sat} \) is the amplifier input saturation voltage, \( p \), is called "knee factor", that controls the smoothness of the transition from the linear region to the saturation region (Limiting Region) of characteristic curve (a typical value of \( p = 1 \)). As the value of \( p \) increases, the SSPA model approaches the limiter model [9, 10].

III. SMRCM CBC ITERATIVE RECEIVER STRUCTURE

The decoding/detection principle discussed below is derived based on the similarity between the superposition coding scheme and the Interleave Division Multiple Access scheme (IDMA) [13]. The receiver is assumed to have perfect knowledge of the channel state information. The received signal is processed iteratively, since there are large numbers of interference terms, the Gaussian approximation is still valid even after last iteration. The received signal at time instant \( j \) can be written as:

\[ r_j = x_j + n_j, j = 1,2,\ldots,J \]  \hspace{1cm} (5)

Where, \( x_j \) denoted the transmitted data symbols for the user at time instant \( j \), and \( n_j \) zero mean AWGN with

\[ \sigma^2 = \frac{N_0}{2} \]

![Receiver](image)

Figure 2. Receiver structures of the proposed SMRCM

The CBC iterative receiver, in Fig.2, consists of an Elementary Signal Estimator (ESE) and a bank of \( k \) single user a posteriori probability detectors for the De-Spreading operation (DES) working in turbo type manner [14]. The DES performs a coarse CBC estimation. The received signal at time instant \( j \) can be re-written as:

\[ r_j = F \left( \sum_{k=1}^{K} \beta^k x^k_j \right) + \xi^k_j \]

Where, \( \xi^k_j = n_j - \beta^k x^k_j \), represents a distortion term with respect to \( x^k_j \), is treated as a random variable with mean \( E(x^k_j) \) and variance \( \text{Var}(x^k_j) \). The initial values for both mean \( E(x^k_j) \) and variance \( \text{Var}(x^k_j) \) are "0" and "1" respectively. Then form "(6)", we can write:

\[ E(r_j) = \sum_{k=1}^{K} \theta^k E(x^k_j) \]  \hspace{1cm} (7a)

\[ \text{Var}(r_j) = \sum_{k=1}^{K} \beta^k \text{Var}(x^k_j) + \sigma^2 \]  \hspace{1cm} (7b)

Using the central limit theorem, \( \xi^k_j \) in "(6)" can be approximated by a Gaussian random variable with:

\[ E(\xi^k_j) = E(r_j) - \beta^k E(x^k_j) \]  \hspace{1cm} (8a)

\[ \text{Var}(\xi^k_j) = \text{Var}(r_j) - \beta^k \text{Var}(x^k_j) \]  \hspace{1cm} (8b)

The ESE outputs are the Logarithm Likelihood Ratio (LLRs) about \( \{x^k_j\} \) computed based on "(7-8)" as:

\[ L(x^k_j) = \log \left( \frac{\Pr(x^k_j = +1 | r_j)}{\Pr(x^k_j = -1 | r_j)} \right) \]

\[ = \log \left( \frac{\exp\left(\frac{-(r_j) - E(x^k_j) - \beta^k}{2\text{Var}(x^k_j)}\right)}{\exp\left(\frac{-(r_j) - E(x^k_j) + \beta^k}{2\text{Var}(x^k_j)}\right)} \right) \]

\[ = \frac{2\beta^k (r_j - E(x^k_j))}{\text{Var}(x^k_j)} \]  \hspace{1cm} (9)

For the layer \( k \), the corresponding ESE outputs \( L(x^k_j, j = 1,2,\ldots,J) \), are de-interleaved to form \( L(C^k_j, j = 1,2,\ldots,J) \), and delivered to the DSE for layer \( k \). The DES performs a soft in soft out CBC DES operation. For simplicity, we focus on the chip related to \( d^k_j \),
the first bit of layer \( k \). It is assumed that, \( L(C_j^k) \) are uncorrelated due to interleaving [13]. Let the interleaving for layer \( k \) be expressed as \( \pi_j^k = j^* \), i.e., \( C_j^k = x_{j^*}^k \). Then based on “(9)”, a posteriori LLR for \( \alpha_{i1}^k \) can be computed using \( L(C_j^k) \) as:

\[
L(d_{j1}^k) = \log \left( \frac{\Pr(d_{j1}^k = +1 | r_j)}{\Pr(d_{j1}^k = -1 | r_j)} \right)
\]

\[
= \log \left( \frac{\prod_{j=1}^{s} \Pr(C_j^k = S_j^k | r_j)}{\prod_{j=1}^{s} \Pr(C_j^k = -S_j^k | r_j)} \right)
\]

\[
= \sum_{j=1}^{s} \log \frac{\Pr(C_j^k = S_j^k | r_j)}{\Pr(C_j^k = -S_j^k | r_j)}
\]

\[
= \sum_{j} S_j^k L(C_j^k)
\]

The Extrinsic LLRs \( \{\text{Ext}(C_j^k)\} \) form the output of the DES and are fed back to the ESE after interleaving. In the next iteration, \( \{\text{Ext}(x_j^k)\} \) and \( \{\text{Var}(x_j^k)\} \) are used to update \( \{E(x_j^k)\} \) and \( \{\text{Var}(x_j^k)\} \) as [12].

\[
E(x_j^k) = \left( \frac{\exp(\text{Ext}(x_j^k)) - 1}{\exp(\text{Ext}(x_j^k)) + 1} \right)
\]

\[
\text{tanh} \left( \frac{E(x_j^k)}{2} \right)
\]

\[
\text{Var}(x_j^k) = 1 - E(x_j^k)^2
\]

This iterative process is repeated a preset number of times. In the final iteration the DES produces hard decisions on information bits \( \overline{d}_1 \) which is re-partitioned into \( k \) subsequences, \( \left\{ \overline{d}_1 = \overline{d}_{11}, \ldots, \overline{d}_{1k} \right\} \), the \( k \) subsequences are decoded by a different rate convolutional decoders at the \( k \) levels, resulting in a sequences \( \left\{ \overline{d}_{11}, \ldots, \overline{d}_{1k} \right\} \), and then concatenated together to reconstruct the user data transmitted.

IV. PERFORMANCE EVALUATION

In this section, the numerical results demonstrate the performance of the proposed SMRCM system. The user data length is assumed to be \( (N = 384) \) bit length partitioned into two bit streams or two layers \( (L = 2) \), based on data priority, the encoding process is applied. The same spreading code is used for all layers, it contains \( (S = 16) \) balanced sequences. The number of iterations in the CBC iterative receiver was set to \( (I_{\text{iter}} = 3) \).

For the HPA linearity, an ideal amplifier would be a totally linear response device, but real amplifiers are only linear response within certain practical limits, so, the HPA non-linearity behavior can be investigated at different smoothness factors. Fig. 3 shows the relationship between input voltage and output voltage linear response and non-linear response at different HPA smoothness factors \( (\rho = 1, 2, 3, 100) \).

The simulation has four cases, the first case is USM, where, the user data length is equally partitioned into two bit streams, each one is \( 192 \) bit length and no convolutional encoders are used, it can be written in the form USM \((192, 192)\). The second case is UEP-SCM, where the user data length is unequally partitioned into two layers, the HP data stream is \( 128 \) bit length, convolutionally coded with rate, \((R = 1/2)\), while the LP data stream is \( 256 \) bit length and has no coding, it can be written in the form UEP-SCM \((128, 256)\), based on data priority, the following formula can be written, UEP-SCM \((96, 288)\).

The third case is EEP-SCM, where the user data length is equally partitioned into two bit streams, each one has the same priority, so, using equal error rates convolutional encoders, it can be written in the form, EEP-SCM \((192, 192)\) and EEP-SCM \((192/3, 192/3)\), to study the effect of different rate convolutional encoders.

Finally, the fourth case, Multi Rate input and Multi Rate Coding, where the user data input is un-equally partitioned into two layers, HP data stream is \( 128 \) bit length, convolutionally encoded with rate, \((R = 1/3)\), while the LP is \( 256 \) bit length, encoded with rate, \((R = 2/3)\), SMRCM symbols can be written in the form, SMRCM \((128, 256, 256)\). All the previous cases are investigated over AWGN channel, and re-investigated in the presence of SSPA over Rayleigh fading channels.

The simulation results for AWGN channel are shown in Fig. (4-6). Fig. 4 shows the UEP-SCM performance is better than USM by about \( 0.7 = 0.8 \) dB at \( \text{BER} = 10^{-1} \) due to the effect of UEP effect. Fig. 5 shows the performance comparison between USM and EEP-SCM. EEP-SCM
Fig. 6 shows the performance comparison between USM, UEP-SCM and EEP-SCM compared with the proposed SMRCM at different code rates, where, the proposed SMRCM is better than USM by 3.3 dB at BER = 10^{-4} due to the effect of MR Coding, the proposed SMRCM performance is better than UEP-SCM by 2.8 dB at BER = 10^{-4}. Note that, the proposed SMRCM performance is degraded by about 0.3 dB compared with EEP-SCM.

The simulation results for AWGN channel in the presence of HPA are shown in Fig. (7-8). Fig. 7 shows the performance comparison between USM, UEP-SCM and EEP-SCM compared with the proposed SMRCM at different code rates. The effect of HPA non-linearity behavior is clear, at the same $E_b/N_0 = 18$ dB, the BER performance of USM and UEP-SCM is $6.82 \times 10^{-4}$, $3.75 \times 10^{-4}$ respectively, while the effect of the EEP and the proposed MR Coding at BER = 10^{-4}, the values are, 11.2 dB and 12 dB respectively, i.e., the proposed SMRCM performance is degraded by 0.8 dB.

Fig. 8 shows the effect of different smoothness factor values ($p = 1, 2, 3, 100$) of non-linear HPA Rapp model on the SMRCM performance. The SMRCM performance is degraded with decreases the $p$ values. Fig. 9 shows the performance comparison between USM, UEP-SCM and EEP-SCM compared with the proposed SMRCM at different code rates in the presence of HPA over Rayleigh fading channel at $90 \text{ km/hr}$ .

In Fig. 9, the effect of HPA non-linearity behavior over the Rayleigh fading channel is clear, at $E_b/N_0 = 18$ dB, the BER performance of USM and UEP-SCM is degraded to $0.9 \times 10^{-4}$, $4.6 \times 10^{-4}$ respectively, while the HPA effect on EEP-SCM and the proposed SMRCM is $1.03 \times 10^{-4}$ and $3.5 \times 10^{-5}$ respectively, i.e., the difference between the proposed SMRCM and EEP-SCM is $6.8 \times 10^{-3}$.
In this paper, a novel SMRCM communication system has been investigated. In the proposed SMRCM, the user data stream is un-equally partitioned based on data priority. Simulation results for the proposed SMRCM are compared with the three systems USM, UEP-SCM and EEP-SCM over AWGN channel. Also, the performances of all systems have been studied in the presence of HPA Rapp model and Rayleigh fading channels. In AWGN channel, the performance of the proposed SMRCM is better than USM by about 3.3 dB. Also, the proposed SMRCM is better than UEP-SCM by 2.3 dB. The performance of the proposed SMRCM is degraded by about 0.3 dB compared with EEP-SCM. All comparisons have been investigated.
been studied at $BER = 10^{-5}$. In HPA, the proposed SMRCM performance is better than USM and UEP SCM by 2.7 dB, 1.6 dB at $BER = 10^{-6}$ respectively, but degraded by about 0.5 dB compared with EEP-SCM at $BER = 10^{-6}$. The BER performances of USM, EEP-SCM and the proposed SMRCM have been studied in Rayleigh fading channel effect at velocity $90 \text{ km/hr}$.

VI. REFERENCES


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