ROBUST TRANSMISSION OF MULTIMEDIA
COMPRESSED STREAMS OVER BAND-LIMITED
WIRELESS CHANNELS USING WAVELET PACKET
DIVISION MULTIPLEXING

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Abstract

Due to the extensive use of predictive coding, multimedia compressed
streams exhibit different sensitivities to transmission errors. Therefore,
they are suitable for unequal error protection (UEP) techniques which
aim at preserving the integrity of sensitive data. UEP is mainly based
on differentiated error control coding which raises the robustness of
data, but also increases the transmission bandwidth. However, the
design of efficient wireless communication systems is often complicated
by stringent bandwidth constraint. This work proposes a general
framework for efficient and robust transmission of multimedia
compressed streams over band-limited wireless channels. To cope with
bandwidth restriction wavelet packet orthogonally overlapped
modulation with unequal power allocation (UPA) is used for UEP of
data. Performance is tested over AWGN and frequency flat Rayleigh's slow fading channel, which well model the transmission conditions typical in most wireless communication standards such as WiFi and Bluetooth.

1. Introduction

The widespread use of multimedia mobile communications for both personal and business purposes is expected to significantly intensify, in the near future, the transmission of multimedia data over wireless channels. It is likely that it will be generated a strong demand for wireless devices able to efficiently transmit data such as images and video contents. In this context, a crucial point for the overall performance of the above devices is the quality of the data delivered to the end user. Within this framework, compression techniques are necessary to reduce the needs in terms of bandwidth, while ensuring acceptable reconstruction quality. Due to the extensive use of predictive and variable length codes, a compressed stream is in general more vulnerable to data losses and transmission errors, which can desynchronize the decoder causing spatial and temporal error propagation. This is the case of digital multimedia compressed streams such as JPEG or MPEG [9] which exhibit different sensitivities to transmission errors. Unequal error protection (UEP) is a channel coding technique used to increase the robustness of data which exhibit different sensitivities to transmission errors. Since, in wireless transmission feedback channel is rarely available, UEP relies on differentiated forward error correction (FEC) coding [2]. Depending on their sensitivities to channel errors, data are protected with codes with higher or lower error correction capabilities. Reed-Solomon (RS) or Turbo Codes (TC) is frequently used ([1], [7]). Unequal power allocation (UPA) is an alternative UEP technique which is deployed when, for several reasons, FEC coding is not efficient [3]. In most wireless communication systems (e.g., DECT, Bluetooth), the available channel bandwidth is a key constraint and the use of FEC-based UEP schemes is weak, or sometimes avoided, as inevitably impairs the transmission efficiency. In fact, FEC is a discrete nature coding scheme. It is subjected to some constraint which restricts the protection
level (i.e., the coding rate) only to a set of fixed values. Therefore, the overhead introduced by FEC codes can be a significant limitation for the efficient use of the bandwidth. On the other hand, UPA distributes the available budget power over the parts of the stream, according to their sensitivities to channel error: to more sensible data is assigned higher transmission power. As a result, it allows achieving improved final quality on transmitted data without any increase of the transmission bandwidth. In practice, UPA is performed by assigning different power weights to the data according to their “importance” (i.e., channel error sensitivities) within the stream. As to this, UPA is a “continuous” process in the sense that weights are chosen in a real set with an accuracy which can be a priori selected and in theory infinite.

Wavelet packet modulation for orthogonally multiplexed communication was introduced as a promising technique to improve performance of conventional FDM and TDM schemes [5]. The properties of wavelet packets are exploited to embed data into waveforms which are mutually orthogonal both in time and frequency. The overlapping bandpass nature of such transmission pulses allows better exploitation of the bandwidth respect to classical FD, as well as intrinsically mitigates fading effects [10].

In this work, we propose a general UPA scheme for wavelet packet division multiplexing (WPDM), which can increase the resilience of compressed streams during their transmission over error prone band-limited wireless channels. Rather than considering the transmission of a specifically formatted stream, we derive a framework for generic correlated data as composed by more sensible parts which need accurate protection. UPA applied to WPDM consists on assigning different power to wavelet packets according to the importance of the message signals carried on. In other words, considering a generic bit pattern, individual bits are weighted differently taking the channel conditions into account and then transmitted on separate wavelet packets. The least significant bit (LSB) gets less energy than the most significant bit (MSB), while the average transmitted energy per bit remains unaffected. As to the weights optimization we use the minimum mean square error (MMSE) between the transmitted and decoded bit pattern.
Results show that the proposed UPA-WPDM scheme allows increasing resilience of data which exhibit different sensitivities to channel errors during their transmission over band-limited wireless channels. The performance improvement in terms of quality measured on received data has been proved against an equally distributed power WPDM scheme and an FEC-based UEP system in the presence of similar bandwidth constraint. Moreover, the bandwidth gain for target quality has been evaluated beside UEP FEC-based techniques.

In the following section an overview on the WPDM technology is given. Section 3 formally defines UPA for WPDM by describing in detail the weighting optimization procedure for Rayleigh fading channel in the presence of AWGN. The experimental results are discussed in Section 4.

2. Wavelet Packet Division Multiplexing

WPDM is a multiple signal transmission technique in which the message signals are waveform coded onto wavelet packet basis functions for transmission. To define the wavelet packet basis functions we refer to wavelet multiresolution analysis (MRA), the details of which can be found in ([4], [6]).

Let \( g_0[n] \) be a unit-energy real causal FIR filter of length \( N \) which is orthogonal to its even translates, i.e., \( \sum_n g_0[n] g_0[n - 2m] = \delta[m] \), where \( \delta[m] \) is the Kronecker delta, and let \( g_1[n] \) be the (conjugate) quadrature mirror filter (QMF), \( g_1[n] = (-1)^n g_0[N - 1 - n] \). If \( g_0[n] \) satisfies some mild technical conditions [4], we can use an iterative algorithm to find the function \( \phi_{01}(t) = \sqrt{2} \sum_n g_0[n] \phi_{01}(2t - nT_0) \) for an arbitrary interval \( T_0 \).

Subsequently, we can define the family of functions \( \phi_{lm} \), \( l \geq 0, 1 \leq m \leq 2^l \) in the following (binary) tree-structured manner:

\[
\begin{align*}
\phi_{l+1,2m-1}(t) &= \sum_n g_0[n] \phi_{lm}(t - nT_l), \\
\phi_{l+1,2m}(t) &= \sum_n g_1[n] \phi_{lm}(t - nT_l),
\end{align*}
\]

where \( T_l = 2^l T_0 \). For any given tree structure, the function at the leaves
of the tree form a *wavelet packet*. They have a finite duration, \((N - 1)T_f\), and are self- and mutually-orthogonal at integer multiples of dyadic intervals, and hence they are a natural choice for scalable multiplexing applications [10]. In Figure 1 the eight wavelet packet functions \((a)\) and the relevant power spectrum \((b)\) for three level standard 12-tap Daubechies filters decomposition.

In WPDM binary messages \(x_{lm}[n]\) have polar representation (i.e., \(x_{lm}[n] = \pm 1\)), are waveform coded by pulse amplitude modulation (PAM) of \(\phi_{lm}(t - nT_f)\) and then added together to form the composite signal \(s(t)\). WPDM can be implemented using a transmultiplexer and a single modulator [10] as Figure 2 illustrates for a two level decomposition. In this case

\[
s(t) = \sum_k x_{01}[k]\phi_{01}(t - kT_0),
\]

where \(x_{01}[k] = \sum_{(l,m)\in\Gamma} \sum_n f_{lm}[k - 2^l n]\), with \(\Gamma\) being the set of terminal index pairs and \(f_{lm}[k]\) the equivalent sequence filter from the \((l, m)\)-th terminal to the root of the tree, which can be found recursively from (1). The original message can be recovered from \(x_{01}[k]\) using

\[
x_{lm}[n] = \sum_k f_{lm}[k - 2^l n]x_{01}[k].
\]

### 3. Unequal Power Allocation for WPDM

Without loss of generality to model a generic bitstream which exhibits different error sensitivities to channel conditions, we consider a discrete periodic (period \(\tau\)) memoryless source \(S : \forall \tau \rightarrow u(\tau)\) and an analog to digital process \(AD : \forall u(\tau) \rightarrow x(\tau)\) with \(x(\tau) \in \{x_k | k = 1, 2, \ldots, 2^M\}\), \(x_k = (x_k^{(1)}, x_k^{(2)}, \ldots, x_k^{(M)})\), \(x_k^{(M)}\) being the LSB. Each \(x_k^{(i)}\) is then multiplied with the specific weight \(w_i \in \mathbb{R}^+\) of the diagonal matrix \(W = \text{diag}(w_1, w_2, \ldots, w_M)\). The weighted bit pattern \(\gamma(\tau) = W \cdot x(\tau)\) is then transmitted by an \(M\)-th order WPDM over a wireless channel affected by additive white Gaussian noise (AWGN) \(n(t)\) with zero mean and variance \(N_0/2\).
If the duration of a modulated symbol is much greater than the delay spread caused by multipath propagation, in case of slow relative motion between transmitter and receiver, the signal at the receiver front end is

\[ r(t) = \Re e^{j\Theta} s(t) + n(t) \]

with \( s(t) \) as in (1) and \( T_0 = 2^{-1}\tau \), and where \( \Re e^{j\Theta} \) is a Gaussian RV with \( \Theta \) uniformly distributed and \( R \) has a Rayleigh p.d.f. in case of non line-of-sight propagation [2]:

\[
f_R(r) = \begin{cases} 
\frac{r}{\sigma^2} e^{-r^2/2\sigma^2}, & 0 \leq r \leq \infty, \\
0, & r < 0.
\end{cases}
\]  

These conditions are likely in WLAN transmission, for instance. In the following we assume perfect channel state information (CSI), (i.e., precise knowledge of the value taken by \( R \)) which allows exact computation of the error probability.

After demodulation, the distributed vector is

\[ \bar{z}(\tau) = \bar{y}(\tau) + \bar{n}_{rel}(\tau), \]

where \( \bar{n}_{rel} = (n_{rel}^{(1)}, n_{rel}^{(2)}, ..., n_{rel}^{(M)}) \), represents the demodulated noise along the \( M \) signal message components (i.e., relevant noise). Following decision based on Maximum Likelihood (ML) criterion, the estimate \( \hat{\tau} \) is produced by inverse digital to analog (DA) process. A sketch of the system is depicted in Figure 3.

A. Weight optimization

Considering bipolar binary representation \( x_k^{(i)} \pm 1 \), if bits in \( \bar{x}(\tau) \) are inverted due to channel impairment, a wrong decision \( \hat{x}(\tau) \) is made at the receiver, thus producing a distortion \( d(\tau) = [u(\tau) - \hat{u}(\tau)] \). Aim of the optimization process is to calculate optimal weights in the sense of a minimized expected value \( E\{[d^2(\tau)]\} \). Assuming ergodicity, it is possible to calculate \( E\{d^2\} \) as follow:

\[
E\{d^2\} = \sum_{k=1}^{M} \sum_{h=1}^{M} d_{k, h}^2 P(\bar{x}_k) \cdot P(\bar{x}_h | \bar{x}_k),
\]

where \( d_{\zeta, \eta} = u_{\zeta} - \hat{u}_{\eta} \) are the different possible parameter values, \( P(\bar{x}_k) \)
is the occurrence of the reproduction levels $u_k$, and $P(\hat{x}_h | x_h)$ is the transition probabilities between transmitted and received bit patterns. Due to the orthogonal properties of WPDM waveforms and to the independence of the noise samples, the transition probabilities are [2]:

$$P(\hat{x}_h | x_h) = \left( \prod_{i=1}^{M} P_b^{(i)} \right) \cdot \left( \prod_{i=1}^{M} (1 - P_b^{(i)}) \right).$$ \hspace{1cm} (6)

Within the UPA framework, under the hypothesis of average energy normalized transmitted frames

$$E_b = \frac{1}{M} \sum_{i=1}^{M} E_b^{(i)} = 1,$$ \hspace{1cm} (7)

we can write [3] $E_b^{(i)} = w_i^2 E_b$ and impose the following constraint on the weights $w_i$

$$\sum_{i=1}^{M} w_i^{\beta} = M.$$ \hspace{1cm} (8)

Being binary amplitude modulation with antipodal symbols the core of WPDM the bit error probabilities in (6) are [2]

$$P_b^{(i)} = \frac{1}{2} \left( 1 - \frac{w_i^2 E_b / N_0}{\sqrt{1 + w_i^2 E_b / N_0}} \right).$$ \hspace{1cm} (9)

where $E_b = E[R^2] E_b = 2\sigma_r^2$ as from (4) and (7).

Mathematically, the optimization problem is to minimize (5) under the constraint (8). In other words, UPA raises ($w_i > 1$) the immunity to channel impairment for more significant bits, paying as a counterpart lower robustness ($w_i < 1$) on less significant one, to achieve average improved performance on the transmission of parameter $u(\tau)$ in the sense of minimum expected distortion $d(\tau) = [u(\tau) - \hat{u}(\tau)]$. 
The complexity of the above optimization problem, which increases with the frame size \( M \), does not allow closed form solutions. Therefore, to identify the solution, we use a numerical approach based on Lagrange Multipliers.

**B. Lagrange multipliers**

Lagrange multiplier is a method for finding the extrema of a function of several variables subject to one or more constraint: it is the basic tool in nonlinear constrained optimization. It replaces finding stationary points of a constrained function in \( n \) variables with \( h \) constraints to finding stationary points of an unconstrained function in \( h + n \) variables: the method introduces a new unknown scalar variable (the Lagrange multiplier \( \lambda \)) for each constraint and defines a new function (the Lagrangian) in terms of the original function, the constraints, and the Lagrange multipliers. In our case, \( n = M, \ h = 1 \) and we can define a nonlinear function \( L: \mathbb{R}^{M+1} \to \mathbb{R} \) with \( M + 1 \) variables which are the \( M \) weights \( w_i \) and the Lagrange multiplier \( \lambda \).

\[
L(w_1, w_2, ... w_M, \lambda) = \left( \sum_{k=1}^{M} \sum_{h=1}^{M} d_{k,h}^2 P(x_k) \cdot P(x_h | x_k) \right) + \lambda \left( \sum_{i=1}^{M} w_i^2 - M \right). \tag{10}
\]

Then we calculate the \( M + 1 \) roots of

\[
\nabla[L(w_1, w_2, ... w_M, \lambda)] = 0
\tag{11}
\]

for \( \lambda \neq 0 \). In mathematics, Newton’s method is a well-known iterative algorithm for finding roots of equations in one or more dimensions. If we define \( z = (w_1, w_2, ... w_M, \lambda) \) we can write the iterative scheme as

\[
z_{k+1} = z_k - H^{-1}[L(z_k)] \cdot \nabla L(z_k)
\tag{12}
\]

with \( k \) iteration counter and where \( H^{-1}[\cdot] \) denotes the inverse.

**Hessian** matrix which is the square matrix of second order partial derivatives. When the exit condition \( \| z_{k+1} - z_k \| < \varepsilon \) is satisfied the extremum \( z \) is a local or global minimum for \( L \).
4. Results

A three level WPDM system which deploys packets of size $M = 8$ is used for experiments. To guarantee short delay, standard Daubechies minimum-phase scaling filters [4] filters of length $N = 12$, are deployed. Without loss of generality, to model the parameter $u(\tau)$ delivered at time $\tau$ we use zero-mean $(\eta_\tau = 0)$ Gaussian source $S$ with unitary variance $(\sigma^2_\tau = 1)$. AD/DA processes deploy natural binary mapping based on uniform quantizers. A precision of $\varepsilon = 10^{-12}$ was set as exit threshold for the numerical solution of the optimization problem as in Section 3.B. Table I summarizes the parameter setting for the experiments.

In Figure 4 is shown how for severe channel conditions the weights relevant to more significant bits (i.e., $w_1, w_2$) are emphasized respect to all the others. For $P_b$ approaching $10^{-3}$ a decrease of the above weights corresponds to an increase of $w_3$ which become also higher than 1. For $P_b < 10^{-5}$ all the weights converge to equal unitary value, but still remaining slightly different for $P_b > 10^{-6}$.

Figure 5 shows the improvement achieved by the proposed UPA respect to a benchmark equal power allocation (EPA) WPDM system and against an UEP scheme based on RS(38, 32) codes. UEP is implemented by protecting data with codes with higher or lower coding rate (i.e., the ratio between information and total bits per codeword), according to their sensitivities to channel errors. Here RS (38, 32) indicates averaging coding rate $R_c = 32/38 = 0.84$, which corresponds to an increase of the total bandwidth of about 18%. Achieved quality in the parameters domain is expressed in terms of the signal to noise ratio $SNR_b[dB] = 10 \cdot \log_{10} \frac{[E[u^2(\tau)]]}{[E[(u(\tau) - \hat{u}(\tau))^2]]}$, which is evaluated at varying average bit error probabilities $P_b = (1/M) \sum_{i=1}^{M} P_b^{(i)}$ with $P_b^{(i)}$ as in (9).

UPA outperforms EPA along all the variation range of the average bit error probability within the transmitted frame with a peak gain of 6.84 dB at $P_b = 10^{-3}$. Same behaviour is noticeable respect to RS coding for
\( P_b > 10^{-4} \), with 3.57 dB peak gain for \( P_b = 3.5 \times 10^{-3} \). For \( P_b < 10^{-5} \) all the systems perform similarly with slight prevalence of the RS coding. Mainly, the UPA prevalence for bad channel condition is due to the capability of the optimization procedure to obtain high accuracy by selecting weights in a continuous range of real values. Figure 6 shows the percentage bandwidth gain achieved by UPA respect to UEP based on RS coding for target quality (i.e., fixed \( u\text{SNR}_u \)) on the transmitted parameter \( u(\tau) \) and fixed channel error rate \( P_b = 10^{-4} \). A minimum bandwidth gain above 20\% is noticeable whereas high variations are observed at varying \( SNR_u \). This is due to the discrete nature of RS codes, which are constrained to only a definite set of possible coding rate. On the other hand, UPA is a continuous process which guarantees more flexibility in the protection of sensitive data.

References

Figure 1. (a) Time and (b) frequency portrait for 12-tap Daubechies wavelet packets.

Figure 2. Transmitter and receiver for two level WPDM system.

Figure 3. System model for UPA-WPDM.

Figure 4. Weights values at varying channel conditions.
Figure 5. Measured quality on reconstructed data at varying channel error rate.

Figure 6. Percentage bandwidth gain for fixed quality on the transmitted parameter $u(\tau)$ achieved by UPA against UEP by RS codes.

Table I. Parameters setting for experiments

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>Source</td>
<td>Gaussian ($\eta_s = 0$, $\sigma_s^2 = 1$)</td>
</tr>
<tr>
<td>$AD/DA$</td>
<td>analog to digital/digital to analog processes</td>
<td>uniform quantizer, natural binary mapping</td>
</tr>
<tr>
<td>$M$</td>
<td>bit frame size</td>
<td>8</td>
</tr>
<tr>
<td>$w_i$</td>
<td>weights</td>
<td>$\in \mathbb{R}^+$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>exit threshold</td>
<td>$10^{-12}$</td>
</tr>
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