Study of Certain Subband-based Adaptive Modulation Schemes in an OFDM System

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Abstract — In applying adaptive schemes to an OFDM system to adaptively adjust the transmission format based on channel state information, a practical scheme would group the subcarriers into similar-quality subbands to reduce the associated modem mode-signaling requirements. One way to determine the modulation mode for a specific subband is based on the average signal-to-noise ratio (SNR) of the subband. To find the optimal switching levels, knowledge of the probability density function of this average SNR is required. Another popular way to determine the modulation mode is based on the SNR of the worst subcarrier of the subband, which may represent an overconservative choice of order statistic. This approach can be extended to deploying other statistic as well, for example, the second or the third worst statistic. Analysis of the above approaches is the focus of this study, and performances of these schemes are compared through numerical simulations.

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For an OFDM system in wireless communication, due to multipath fading, subcarriers experience signal-to-noise ratio (SNR) degradation to varying degree. Adaptive modulation schemes are effective to mitigate such detrimental effect, where in principle the transmitted power and bit rate of each subcarrier are allowed to change dynamically according to channel variations. Yet such a full treatment implies high complexity in modem hardware and high signalling overhead over the feedback channel from the receiver to the transmitter, a scheme that may not be plausible in high-speed wireless data applications. Such concern leads to some suboptimal schemes. Grunheid et al.\textsuperscript{[1]} and Keller and Hanzo\textsuperscript{[2]} proposed to group the subcarriers into similar-quality subbands with single constellation being used for the subcarriers within a subband. Dardari\textsuperscript{[4]} proposed an ordered subcarrier selection algorithm where among the available $N$ subcarriers only the $K$ subcarriers ($K \leq N$) with the highest SNRs are used, to which uniform bit and power level allocation are applied.

For a mode-switching-assisted adaptive modulation scheme, the bit-error-rate (BER) and throughput performances are determined by the set of switching levels. Chung and Goldsmith\textsuperscript{[4]} and Choi and Hanzo\textsuperscript{[5]} analyzed for single carrier system the constant power variate rate adaptive modulation scheme. The optimal switching levels that maximize the average bits-per-symbol (BPS) throughput for a target average BER are found to depend on the channel quality statistics. In extending this technique to multicarrier system where subband based adaptive modulation scheme is adopted, Keller and Hanzo\textsuperscript{[2]} proposed to use the subcarrier experiencing the worst SNR. This approach may appear somehow conservative, which motivates us to analyze the problem using other order statistic of the subcarrier SNRs, such as the second or the third worst statistic. Another plausible approach is to use the average SNR of all the subcarriers within a subband, where the optimal switching levels can be determined by using the probability density function (pdf) of the average SNR in conjunction with Lagrangian optimization technique. These approaches form the body of the current study.

In the order statistic approach, the subcarriers are usually assumed to be independently and identically distributed (i.i.d) Rayleigh fading channels for mathematical convenience\textsuperscript{[3]}, although they are in general correlated. Consider a subband containing $P$ subcarriers, where the pdf of the SNR $\gamma$ of each subcarrier is

$$f_\gamma(\gamma) = \frac{1}{\overline{\gamma}} e^{-\frac{\gamma}{\overline{\gamma}}}$$

with $\overline{\gamma}$ being the mean SNR of each subcarrier. The pdf of the $n$th worst order statistic of the subcarrier SNRs is expressed as

$$f_n(\gamma_n) = \frac{P!(1-e^{-\frac{\gamma_n}{\overline{\gamma}}})^{n-1}e^{-\frac{\gamma_n}{\overline{\gamma}}}(P-n+1)}{\overline{\gamma}(n-1)! (P-n)!}.$$
Specifically, the pdfs of the worst, second worst and third worst order statistics are respectively

\[ f_n(\gamma_n) = \frac{P!}{\gamma (n-1)! (P-n)!} \left( 1 - e^{-\frac{\gamma}{\gamma_n}} \right)^{n-1} e^{-\frac{\gamma}{\gamma_n}} \left( P-\gamma_n \right)^{n-1} e^{-\frac{\gamma}{\gamma_n}} \left( P-\gamma_n \right)^{P-n+1} \]  

(3)

\[ f_2(\gamma_2) = \frac{P (P-1)}{2\gamma} \left( e^{-\frac{\gamma}{\gamma_2}} - e^{-\frac{\gamma}{\gamma_2}} \left( P-1 \right) \right) \]  

(4)

and

\[ f_3(\gamma_3) = \frac{P (P-1) (P-2)}{2\gamma} \left( e^{-\frac{\gamma}{\gamma_3}} - 2 e^{-\frac{\gamma}{\gamma_3}} (P-1) + e^{-\frac{\gamma}{\gamma_3}} P \right) \]  

(5)

The optimal switching levels can be thus obtained by making use of the above pdf in conjunction with Lagrangian optimization technique [5].

In the average SNR approach, where the average SNR \( \gamma_a = \frac{1}{P} \sum_{m=1}^{P} \gamma_m \), if SNRs of the subcarriers are still assumed to be i.i.d random variables, then the pdf of \( \gamma_a \) can be expressed as

\[ f_a(\gamma_a) = \frac{\gamma}{\gamma_a} \frac{(\gamma_a)^{P-1}}{P!} e^{-\frac{\gamma}{\gamma_a}} \]  

(6)

However, a more rigorous expression for \( \gamma_a \) where the correlations between subcarriers are accounted for is derived by Du [6] as

\[ f_a(\gamma_a) = \frac{1}{2} \sum_{k=1}^{P} \alpha^2 \exp \left( -\frac{\gamma_a}{2\alpha} \right) \frac{\alpha}{2\alpha} \prod_{r=1, r \neq k}^{P} (\alpha - \alpha_r)^{-1} \]  

(7)

where \( \alpha_k = \frac{\lambda_k}{P\sigma_n^2} \), \( \sigma_n^2 \) is the variance of the AWGN noise, \( \lambda_k \) are the eigenvalues of the covariance matrix of subcarriers.

To study the performance of these two proposed approach, we simulate a MC-SS system where the parameters are given in Table 1. The modulate modes are NO-Transmission, BPSK, QPSK, 16QAM, and 64QAM. The target average BER is \( 10^{-4} \). The channel under consideration is the BRAN-A channel, which has 11 Rayleigh fading paths. Yet the 20 MHz sampling rate of the system cannot completely distinguish these paths, leading to a combination of these paths to six distinguishable paths. Channel estimation is assumed to be ideal. For each BER and throughput data point, 50000 channel realizations are used.

Table 1: MC-SS system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>5.2 GHz</td>
</tr>
<tr>
<td>Mobile Speed</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Number of Rayleigh Fading Paths</td>
<td>11</td>
</tr>
<tr>
<td>Doppler Frequency Shift</td>
<td>14.444 Hz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Bandwidth per Subcarrier</td>
<td>156.25 kHz</td>
</tr>
<tr>
<td>maximum delay</td>
<td>0.243 us</td>
</tr>
<tr>
<td>Size of the FFT</td>
<td>128</td>
</tr>
<tr>
<td>Protecting Interval</td>
<td>5</td>
</tr>
<tr>
<td>Number of Subcarriers per OFDM Symbol</td>
<td>128</td>
</tr>
<tr>
<td>Period of Data Interval</td>
<td>6.40 ms</td>
</tr>
<tr>
<td>Number of Available Subcarriers per OFDM Symbol</td>
<td>96</td>
</tr>
<tr>
<td>Spreading Factor</td>
<td>8</td>
</tr>
</tbody>
</table>

For order statistic based adaptive modulation scheme, Fig. 1 shows the BER performance, where there are six neighboring subcarriers in each subband, resulting in a total of 16 subbands. It is expected that the worse the subcarrier SNR statistic is used, the more conservative thus the better the BER performance. Fig. 1 shows that it indeed is the case. Yet the BER curves also demonstrate distinct feature quite different from that of the single carrier case: the target average BER is achieved for the latter case but not for the former one. The reason for such difference highlights the fact that the BER performance of a multicarrier system is collectively determined by subcarriers (here all subcarriers within a subband), so the BER constraint condition imposed on an individual subcarrier may not be fulfilled collectively.
Figure 1: BER performance for order statistic based adaptive modulation system.

Figure 2: Throughput performance for order statistic based adaptive modulation system.

Figure 3: BER performance for average subband SNR based adaptive modulation system.

Figure 4: Throughput performance for average subband SNR based adaptive modulation system.

REFERENCES

