Time-Variant Bitrate Turbo-Coded Near-Instantaneously Adaptive OFDM-Based Interactive Videophony

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Abstract— **A range of Adaptive Orthogonal Frequency Division Multiplex (AOFDM) video systems are proposed for interactive communications over wireless channels. The proposed constant target bitrate subband adaptive OFDM (CTBR-AOFDM) modems can provide a lower BER, than a corresponding conventional OFDM modem. The slightly more complex switched or Time-Variant Target Bit Rate (TVTBR) AOFDM modems can provide a balanced video quality performance, across a wider range of channel SNRs, maintaining the best video performance. Upon invoking the technique advocated - irrespective of the channel conditions experienced - the transceiver achieves always the best possible video quality by automatically adjusting the achievable bitrate and the associated video quality in order to match the channel quality experienced. This is achieved on a near-instantaneous basis under given propagation conditions in order to cater for the effects of pathloss, fast-fading, slow-fading, dispersion, etc. Furthermore, when the mobile is roaming in a hostile outdoor propagation environment, typically low-order, low-rate modem modes are invoked, while in benign indoor environments predominantly the high-rate, high source-signal representation quality modes are employed.**

I. Motivation and Background

The concept of burst-by-burst adaptive quadrature amplitude modulation [2] (AQAM) was first proposed by Hayes as early as 1968 [1], in order for the transceiver to cope with the time-variant channel quality of fading channels. Over the years substantial advances have been made in this field for example at the University of Osaka by Sampei and his colleagues, investigating variable coding rate concatenated coded schemes [3], at the University of Stanford by Goldsmith and her team, studying the effects of variable-rate, variable-power arrangements [4] and at Southampton University in the UK, investigating a variety of practical aspects of AQAM [2], [5], [6]. The channel's quality is estimated on a burst-by-burst basis and the most appropriate modulation mode is selected in order to maintain the required target bit error rate (BER) performance, whilst maximizing the system's Bit Per Symbol (BPS) throughput. Using this reconfiguration regime the distribution of channel errors becomes typically less bursty, than in conjunction with non-adaptive modems, which potentially increases the channel coding gains [7]. Furthermore, the soft-decision channel codec metrics can be also invoked in estimating the instantaneous channel quality [7], irrespective of the type of channel impairments.

A range of coded AQAM schemes were analysed by Matsuoka *et al* [3], Lau *et al* [10] and Goldsmith *et al* [11]. For data transmission systems, which do not necessarily require a low transmission delay, variable–throughput adaptive schemes can be devised, which operate efficiently in conjunction with powerful error correction codecs, such as long block length turbo codes [31]. However, the acceptable turbo interleaving delay is rather low in the context of low-delay interactive speech. Video communications systems typically require a higher bitrate than speech systems and hence they can afford a higher interleaving delay.

The above principles - which were typically investigated in the context of narrowband modems - were further advanced in conjunction with wideband modems, employing powerful block turbo coded wideband Decision Feedback Equaliser (DFE) assisted AQAM transceivers [7], [8]. A neural-network Radial Basis Function (RBF) DFE based AQAM modem design was proposed in [9], where the RBF DFE provided the channel quality estimates for the modem mode switching regime. This modem was capable of removing the residual BER of conventional DFEs, when linearly non-separable received phasor constellations were encountered.

The above burst-by-burst adaptive principles can also be extended to Adaptive Orthogonal Frequency Division Multiplexing (AOFDM) schemes [12], [2], [5] and to adaptive joint-detection based Code Division Multiple Access (JD-ACDMA) arrangements [13], [5]. The associated AQAM principles were invoked in the context of parallel AOFDM modems also by Czylwik et al [24], Fischer [25] and Chow et al [26]. Adaptive subcarrier selection has been advocated also by Rohling et al [28] in order to achieve BER performance improvements. Due to lack of space without completeness, further significant advances over benign, slowly varying dispersive Gaussian fixed links - rather than over hostile wireless links - are due to Chow, Cioffi and Bingham [26] from the USA, rendering OFDM the dominant solution for asymmetric digital subscriber loop (ADSL) applications, potentially up to bitrates of 54 Mbps. In Europe OFDM has been favoured for both Digital Audio Broadcasting (DAB) and Digital Video Broadcasting [17], [18] (DVB) as well as for high-rate Wireless

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Asynchronous Transfer Mode (WATM) systems due to its ability to combat the effects of highly dispersive channels [19]. The idea of 'water-filling' - as allocating different modem modes to different subcarriers was referred to - was proposed for OFDM by Kalet [27] and later further advanced by Chow et al [26]. This approached was rendered later time-variant for duplex wireless links for example in [12]. Lastly, various OFDM-based speech and video systems were proposed in References [15]-[16], while the co-channel interference sensitivity of OFDM can be mitigated with the aid of adaptive beam-forming [22], [23] in multi-user scenarios.

Our main contribution is that upon invoking the technique advocated - irrespective of the channel conditions experienced - the transceiver achieves always the best possible video quality by automatically adjusting the achievable bitrate and the associated video quality in order to match the channel quality experienced. This is achieved on a near-instantaneous basis under given propagation conditions in order to cater for the effects of path-loss, fast-fading, slow-fading, dispersion, etc. Furthermore, when the mobile is roaming in a hostile outdoor propagation environment, typically low-order, low-rate modem modes are invoked, while in benign indoor environments predominantly the high-rate, high source-signal representation quality modes are employed.

The remainder of this contribution is structured as follows. Section II outlines the architecture of the proposed video transceiver, while Section III quantifies the performance benefits of AOFDM transceivers in comparison to conventional fixed transceivers. In Section IV we proposed time-variant, rather than constant rate AOFDM as a means of more accurately matching the transceiver's throughput to the time-variant channel quality fluctuations, before concluding in Section V.

II. Burst-by-burst Adaptive Video Transceiver

In this study we investigate the transmission of 704x576 pixel Four-times Common Intermediate Format (4CIF) high-resolution video sequences at 30 frames/s using subband-adaptive turbo-coded Orthogonal Frequency Division Multiplex (AOFDM) transceivers. The transceiver can modulate 1, 2 or 4 bits onto each AOFDM sub-carrier, or simply disable transmissions for sub-carriers which exhibit a high attenuation or phase distortion due to channel effects.

A reliable channel quality metric can devised by calculating the expected overall bit error probability for all available modulation schemes M_n in each sub–band, which is denoted by $\bar{p}_e(n) = 1/N_s \sum_j p_e(\gamma_j, M_n)$. For each AOFDM sub–band the modem mode having the highest throughput, while exhibiting an estimated BER below the target value is then chosen. While the adaptation granularity is limited to the sub–band width, the channel quality estimation is quite reliable, even in interference-impaired environments.

Against this background in our forthcoming discussions the design trade-offs of turbo-coded Adaptive Orthogonal Frequency Division Multiplex (AOFDM) wideband video transceivers are presented. We will demonstrate that AOFDM provides a convenient framework for adjusting the required target integrity and throughput both with and without turbo channel coding and lends itself to attractive video system construction, provided that a near-instantaneously programmable rate video codec - such as the H.263 scheme highlighted in the next section - can be invoked.

The H.263 video codec [29] exhibits an impressive compression ratio, although this is achieved at the cost of a high vulnerability to transmission errors, since a run-length coded bitstream is rendered undecodable by a single bit error. In order to mitigate this problem, when the channel codec protecting the video stream is overwhelmed by the transmission errors, we refrain from decoding the corrupted video packet, in order to prevent error propagation through the reconstructed video frame buffer [30]. We found that it was more beneficial in video quality terms, if these corrupted video packets were dropped and the reconstructed frame buffer was not updated, until the next video packet replenishing the specific video frame area was received. The associated video performance degradation was found perceptually unobjectionable for packet dropping- or transmission frame error rates (FER) below about 5%. These packet dropping events were signalled to the remote video decoder by superimposing a strongly protected one-bit packet acknowledgement flag on the reverse-direction packet, as outlined in [30]. Turbo error correction codes [31] were used. The associated parameters will be discussed in more depth during our further discourse.

III. Comparison of subband-adaptive OFDM and fixed mode OFDM transceivers

In order to show the benefits of the proposed subband-adaptive OFDM transceiver, we compare its performance to that of a fixed modulation mode transceiver under identical propagation conditions, while having the same transmission bitrate. The subband-adaptive modem is capable of achieving a low bit error ratio (BER), since it can disable transmissions over low quality sub-carriers and compensate for the lost throughput by invoking a higher modulation mode, than that of the fixed-mode transceiver over the high-quality sub-carriers.

Table I shows the system parameters for the fixed BPSK and QPSK transceivers, as well as for the corresponding subband-adaptive OFDM (AOFDM) transceivers. The system employs constraint length three, half-rate turbo coding, using octal generator polynomials of 5 and 7 as well as random turbo interleavers. Therefore the unprotected bitrate is approximately half the channel coded bitrate. The protected to unprotected video bitrate ratio is not exactly half, since two tailing bits are required to reset the convolutional encoders' memory to their default state in each transmission burst. In both modes a 16-bit Cyclic Redundancy Checking (CRC) is used for error detection and 9 bits are used to encode the reverse link feedback acknowledgement information by simple repetition coding. The feedback flag decoding ensues using majority logic decisions. The packetisation requires a small amount of header information added to each transmitted packet, which is 11 and 12 bits per packet for BPSK and QPSK, respectively. The effective or useful video bitrates for the BPSK and QPSK modes are then 3.4 and 7.0 Mbps.

	BPSK mode	QPSK mode
Packet rate	4687.5 Packets/s	
FFT length	512	
OFDM symbols/packet	3	
OFDM symbol duration	2.6667μs	
OFDM time frame	80 Timeslots = 213μs	
Normalised Doppler frequency, f'_d	1.235×10^{-4}	
OFDM symbol normalised Doppler frequency, F_D	7.41×10^{-2}	
FEC coded bits/packet	1536	3072
FEC-coded video bitrate	7.2Mbps	14.4Mbps
Unprotected Bits/Packet	766	1534
Unprotected bitrate	3.6Mbps	7.2Mbps
Error detection CRC (bits)	16	16
Feedback error flag bits	9	9
Packet header bits/packet	11	12
Effective video bits/packet	730	1497
Effective video bitrate	3.4Mbps	7.0Mbps

TABLE I

System parameters for the fixed QPSK and BPSK transceivers, as well as for the corresponding subband-adaptive OFDM (AOFDM) transceivers for Wireless Local Area Networks (WLANs).

The fixed mode BPSK and QPSK transceivers are limited to one and two bits per symbol, respectively. By contrast, the proposed AOFDM transceivers operate at the same bitrate, as their corresponding fixed modem mode counterparts, although they can vary their modulation mode on a sub-carrier by sub-carrier basis between 0, 1, 2 and 4 bits per symbol. Zero bits per symbol implies that transmissions are disabled for the sub-carrier concerned.

The "micro-adaptive" nature of the subband-adaptive modem is characterised by Figure 1, portraying at the top a contour plot of the channel Signal-to-Noise Ratio (SNR) for each subcarrier versus time. At the centre and bottom of the figure the modulation mode chosen for each 32-subcarrier subband is shown versus time for the 3.4 and 7.0 Mbps target-rate subband-adaptive modems, respectively. The channel SNR variation versus both time and frequency is also shown in a three-dimensional form in Figure 2, which maybe more convenient to visualise. This was recorded for the channel impulse response of Figure 3.

It can be seen that when the channel is of high quality – like for example at about frame 1080 – the subband-adaptive modem used the same modulation mode, as the equivalent fixed rate modem in all subcarriers. When the channel is hostile – like around frame 1060 – the subband-adaptive modem used a lower-order modulation mode in some subbands, than the equivalent fixed mode scheme, or in extreme cases disabled transmission for that subband. In order to compensate for the loss of throughput in this subband a higher-order modulation mode was used in the higher quality subbands.

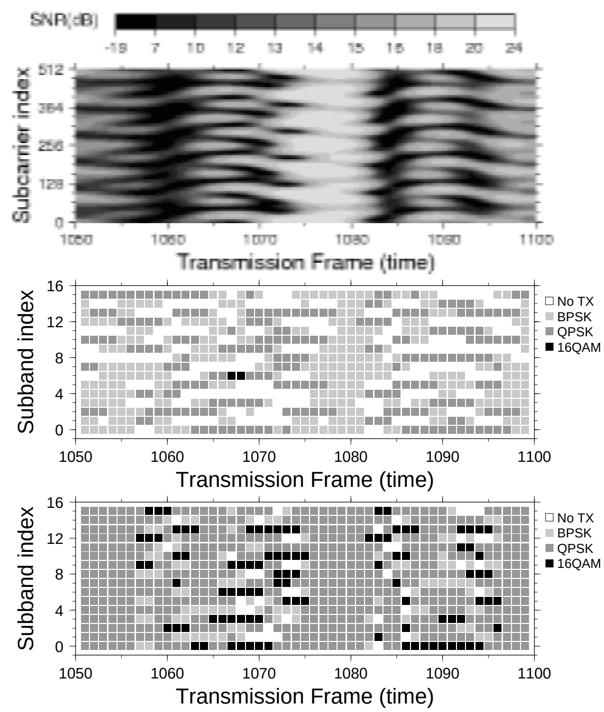


Fig. 1. The micro-adaptive nature of the subband-adaptive OFDM modem. The top graph is a contour plot of the channel SNR for all 512 subcarriers versus time. The bottom two graphs show the modulation modes chosen for all 16 32-subcarrier subbands for the same period of time. The middle graph shows the performance of the 3.4Mbps subband-adaptive modem, which operates at the same bitrate as a fixed BPSK modem. The bottom graph represents the 7.0Mbps subband-adaptive modem, which operated at the same bitrate as a fixed QPSK modem. The average channel SNR was 16dB.

One video packet is transmitted per OFDM symbol, therefore the video packet loss ratio is the same, as the OFDM symbol error ratio. The video packet loss ratio is plotted versus the channel SNR in Figure 4. It is shown in the graph that the subband-adaptive transceivers – or synonymously termed as microscopic-adaptive (μAOFDM), in contrast to OFDM symbol-by-

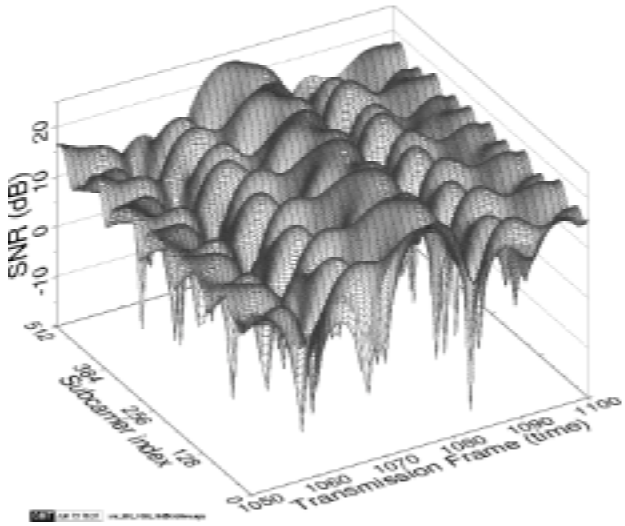


Fig. 2. Instantaneous channel SNR for all 512 subcarriers versus time, for an average channel SNR of 16dB over the channel characterised by the channel impulse response (CIR) of Figure 3.

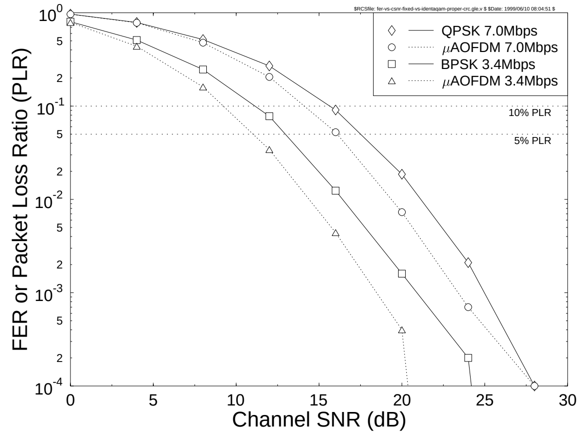


Fig. 4. Frame Error Rate (FER) or video packet loss ratio (PLR) versus channel SNR for the BPSK and QPSK fixed modulation mode OFDM transceivers and for the corresponding subband-adaptive μAOFDM transceiver, operating at identical effective video bitrates, namely at 3.4 and 7.0 Mbps, over the channel model of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

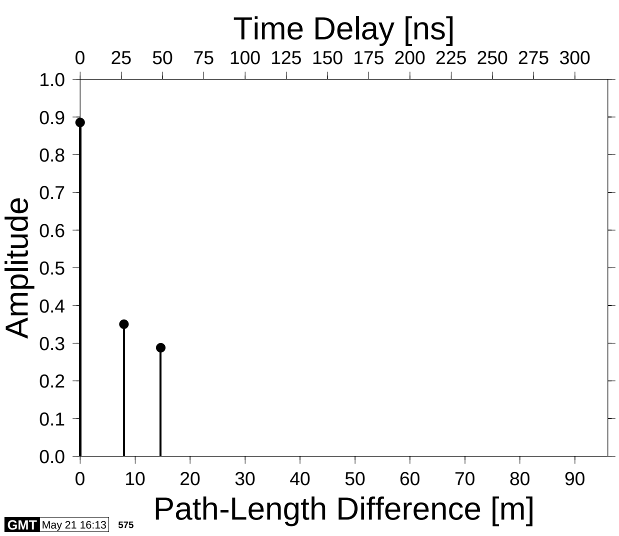


Fig. 3. Indoor three-path WATM channel impulse response.

symbol adaptive transceivers – have a lower packet loss ratio (PLR) at the same SNR compared to the fixed modulation mode transceiver. Note in Figure 4 that the subband-adaptive transceivers can operate at lower channel SNRs, than the fixed modem mode transceivers, while maintaining the same required video packet loss ratio. Again, the figure labels the subband-adaptive OFDM transceivers as μAOFDM, implying that the adaption is not noticeable from the upper layers of the system. A macro-adaption could be applied in addition to the microscopic adaption by switching between different target bitrates, as the longer-term channel quality improves and degrades. This issue is the subject of Section IV.

IV. Time-variant target bitrate OFDM transceivers

Hence below we provide a performance comparison of various μAOFDM transceivers having four different target bitrates, of which two are equivalent to that of the BPSK and QPSK fixed modulation mode transceivers of Table I. The system parameters for all four different bitrate modes are summarised in Table II. The modes having effective video bitrates of 3.4 and 7.0Mbps are equivalent to the bitrates of a fixed BPSK and QPSK mode transceiver, respectively.

By using a high target bitrate, when the channel quality is high, while a reduced target bitrate, when the channel quality is poor, an adaptive system is capable of maximising the average throughput bitrate over a wide range of channel SNRs, while maintaining a given quality constraint. This quality constraint for our video system could be a maximum packet loss ratio.

However, there is a substantial processing delay associated with evaluating the packet loss information and therefore modem mode switching based on this metric would be less efficient due to this latency. Therefore we decided to invoke an estimate of the bit error ratio (BER) for mode switching, which can be estimated as follows. Since the noise energy in each subcarrier is independent of the channel's frequency domain transfer function H_n, the local Signal–to–Noise Ratio SNR in subcarrier n can be expressed as

$$\gamma_n = |H_n|^2 \cdot \gamma, \tag{1}$$

where γ is the overall SNR. If no signal degradation due to Inter–Subcarrier Interference (ISI) or interference from other sources appears, then the value of γ_n determines the bit error probability for the transmission of data symbols over the subcarrier n. Given γ_j across the N_s subcarriers in the j-th sub–band, the expected overall BER for all available modulation schemes M_n in

Packet rate	4687.5 Packets/s			
FFT length	512			
OFDM Symbols/Packet	3			
OFDM Symbol Duration	2.6667μs			
OFDM Time Frame	80 Timeslots = 213μs			
Normalised Doppler frequency, f'_d	1.235×10^{-4}			
OFDM symbol normalised Doppler frequency, F_D	7.41×10^{-2}			
FEC Coded Bits/Packet	858	1536	3072	4272
FEC-coded video bitrate	4.0Mbps	7.2Mbps	14.4Mbps	20.0Mbps
No. of unprotected bits/packet	427	766	1534	2134
Unprotected bitrate	2.0Mbps	3.6Mbps	7.2Mbps	10.0Mbps
No. of CRC bits	16	16	16	16
No. of feedback error flag bits	9	9	9	9
No. of packet header bits/packet	10	11	12	13
Effective video bits/packet	392	730	1497	2096
Effective video bitrate	1.8Mbps	3.4Mbps	7.0Mbps	9.8Mbps
Equivalent modulation mode		BPSK	QPSK	
Minimum channel SNR for 5% PLR (dB)	8.8	11.0	16.1	19.2
Minimum channel SNR for 10% PLR (dB)	7.1	9.2	14.1	17.3

TABLE II

System parameters for the four different target bitrates of the various subband-adaptive OFDM (μAOFDM) transceivers

each sub–band can be estimated, which is denoted by $\bar{p}_e(n) = 1/N_s \sum_j p_e(\gamma_j, M_n)$. For each sub–band, the scheme with the highest throughput, whose estimated BER is lower than a given threshold, is then chosen.

We decided to use a quadruple-mode switched subband-adaptive modem, using the four target bitrates of Table II. The channel estimator can then estimate the expected bit error ratio of the four possible modem modes. Our switching scheme opted for the modem mode, whose estimated BER was below the required threshold. This threshold could be varied in order to tune the behaviour of the switched subband-adaptive modem for a high or a low throughput. The advantage of a higher throughput was a higher error-free video quality at the expense of increased video packet losses, which could reduce the perceived video quality.

Figure 5 demonstrates, how the switching algorithm operates for a 1% estimated BER threshold. Specifically, the figure portrays the estimate of the bit error ratio for the four possible modem modes versus time. The large square and the dotted line indicates the mode chosen for each time interval by the mode switching algorithm. The algorithm attempts to use the highest bitrate mode, whose BER estimate is less than the target threshold namely, 1% in this case. However, if all the four modes' estimate of the BER is above the 1% threshold, then the lowest bitrate mode is chosen, since this will be the most robust to channel errors. An example of this is shown around frames 1035–1040. At the bottom of the graph a bar chart specifies the bitrate of the switched subband adaptive modem versus time, in order to emphasise, when the switching occurs.

An example of the algorithm, when switching amongst the target bitrates of 1.8, 3.4, 7 and 9.8Mbps is shown in

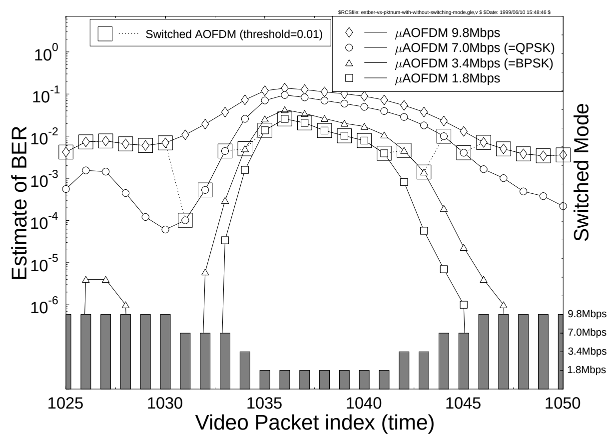


Fig. 5. Illustration of mode switching for the switched subband adaptive modem. The figure shows the estimate of the bit error ratio for the four possible modes. The large square and the dotted line indicate the modem mode chosen for each time interval by the mode switching algorithm. At the bottom of the graph the bar chart specifies the bitrate of the switched subband adaptive modem on the right-hand axis versus time when using the channel model of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

Figure 6. The upper part of the figure portrays the contour plot of the channel SNR for each subcarrier versus time. The lower part of the figure displays the modulation mode chosen for each 32-subcarrier subband versus time for the time-variant target bitrate (TVTBR) subband adaptive modem. It can be seen at frames 1051–1055 that all the subbands employ QPSK modulation, therefore the TVTBR-AOFDM modem has an instantaneous

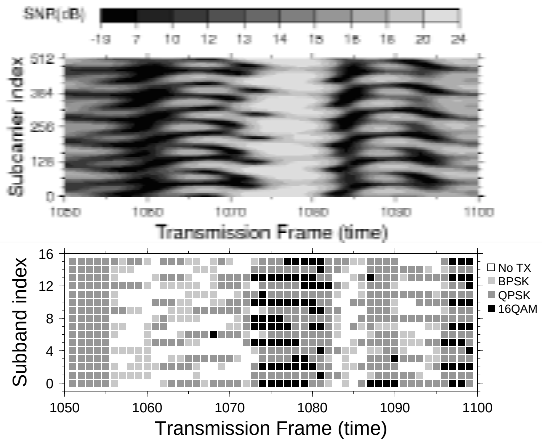


Fig. 6. The micro-adaptive nature of the time-variant target bitrate subband-adaptive (TVTBR-AOFDM) modem. The top graph is a contour plot of the channel SNR for all 512 subcarriers versus time. The bottom graph shows the modulation mode chosen for all 16 subbands for the same period of time. Each subband is comprised of 32 subcarriers. The TVTBR AOFDM modem switches between target bitrates of 2, 3.4, 7 and 9.8Mbps, while attempting to maintain an estimated BER of 0.1% before channel coding. Average Channel SNR is 16dB over the channel of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

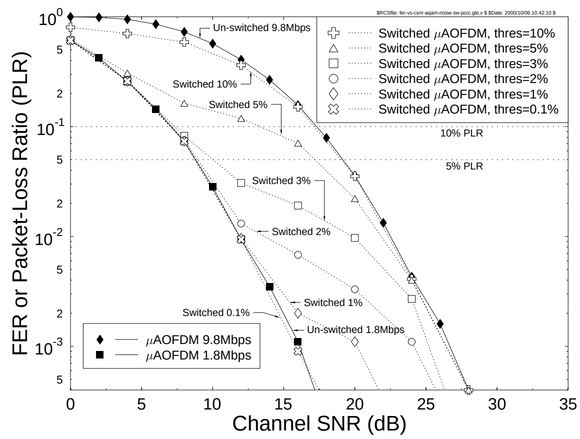


Fig. 7. FER or video packet loss ratio versus channel SNR for the TVTBR-AOFDM modem for a variety of BER switching thresholds. The switched modem uses four modes, with target bitrates of 1.8, 3.4, 7 and 9.8Mbps. The un-switched 1.8 and 9.8Mbps results are also shown in the graph as solid markers using the channel model of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

target bitrate of 7Mbps. As the channel degrades around frame 1060, the modem has switched to the more robust 1.8Mbps mode. When the channel quality is high around frames 1074-1081, the highest bitrate 9.8Mbps mode is used. This demonstrates that the TVTBR-AOFDM modem can reduce the number of lost video packets by using reduced bitrate but more robust modulation modes, when the channel quality is poor. However, this is at the expense of a slightly reduced average throughput bitrate. Usually a higher throughput bitrate results in a higher video quality, however a high bitrate is also associated with a high packet loss ratio, which is usually less attractive in terms of perceived video quality than a lower bitrate, lower packet loss ratio mode.

Having highlighted, how the time-domain mode switching algorithm operates, we will now characterise its performance for a range of different BER switching thresholds. A low BER switching threshold implies that the switching algorithm is cautious about switching to the higher bitrate modes, and therefore the system performance is characterised by a low video packet loss ratio and a low throughput bitrate. A high BER switching threshold results in the switching algorithm attempting to use the highest bitrate modes in all but the worst channel conditions. This results in a higher video packet loss ratio. However, if the packet loss ratio is not excessively high, a higher video throughput is achieved.

Figure 7 portrays the video packet loss ratio or FER performance of the TVTBR-AOFDM modem for a variety of BER thresholds, compared to the minimum and maximum rate un-switched modes. It can be seen that for a conservative BER switching threshold of 0.1% the time-variant target bitrate subband adaptive (TVTBR-AOFDM) modem has a similar packet loss ratio performance to that of the 1.8Mbps non-switched or constant target bitrate (CTBR) subband adaptive modem. However, as we will show, the throughput of the switched modem is always better or equal to that of the un-switched modem, and becomes far superior, as the channel quality improves. Observe in the figure that the "aggressive" switching threshold of 10% has a similar packet loss ratio performance to that of the 9.8Mbps CTBR-AOFDM modem. We found that in order to maintain a packet loss ratio of below 5%, the BER switching thresholds of 2 and 3% offered the best overall performance, since the packet loss ratio was fairly low, while the throughput bitrate was higher, than that of an un-switched CTBR-AOFDM modem.

A high BER switching threshold results in the switched subband adaptive modem transmitting at a high average bitrate. However, we have shown in Figure 7 how the packet loss ratio increases, as the BER switching threshold is increased. Therefore the overall useful or effective throughput bitrate - ie. the bitrate excluding lost packets - may in fact be reduced in conjunction with high BER switching thresholds. Figure 8 demonstrates how the transmitted bitrate of the switched TVTBR-AOFDM modem increases with higher BER switching thresholds. However, when this is compared to the effective throughput bitrate, where the effects of packet loss are taken into account, the tradeoff between the BER switching threshold and the effective bitrate is less obvious. Figure 9 portrays the corresponding effective throughput bitrate versus channel SNR for a range of BER switching thresholds. The figure demonstrates that for a BER switching threshold of 10% the effective throughput bitrate performance was reduced incomparison to some of the lower BER switching threshold scenarios. Therefore the BER=10% switching threshold is obviously too aggressive, resulting in a high packet loss ratio, and a reduced effective throughput bitrate. For the switching thresholds considered, the BER=5% threshold achieved

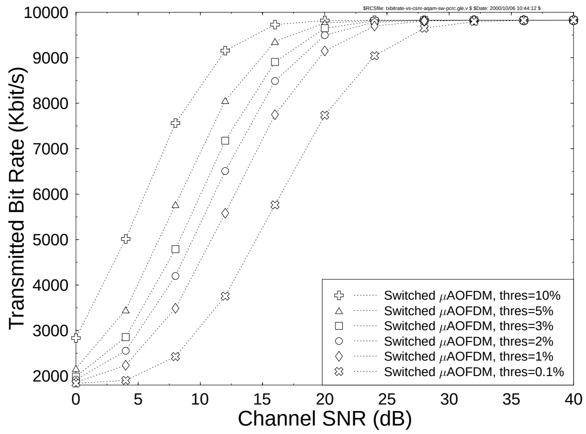


Fig. 8. Transmitted bitrate of the switched TVTBR-AOFDM modem for a variety of BER switching thresholds. The switched modem uses four modes, having target bitrates of 1.8, 3.4, 7 and 9.8Mbps, over the channel model of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

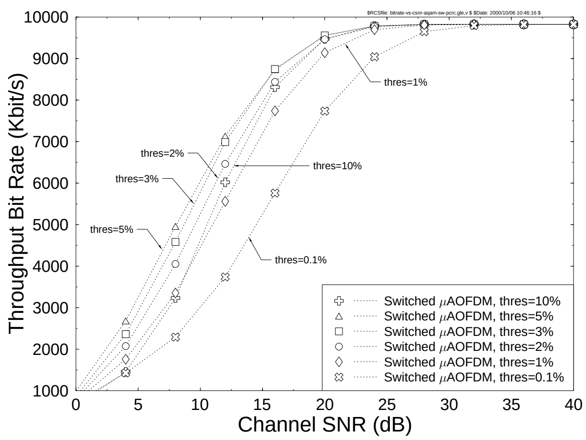


Fig. 9. Effective throughput bitrate of the switched TVTBR-AOFDM modem for a variety of BER switching thresholds. The switched modem uses four modes, with target bitrates of 1.8, 3.4, 7 and 9.8Mbps. The channel model of Figure 3 is used at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

the highest effective throughput bitrate. However, even though the BER=5% switching threshold produces the highest effective throughput bitrate, this is at the expense of a relatively high video packet loss ratio, which – as we will show – has a detrimental effect on the perceived video quality.

We will now demonstrate the effects associated with different BER switching thresholds on the video quality represented by the peak-signal-to-noise ratio (PSNR). Figure 10 portrays the PSNR and packet loss performance versus time for a range of BER switching thresholds. The top graph in the figure indicates that for a BER switching threshold of 1% the PSNR performance is very similar to the corresponding error-free video quality. However, the PSNR performance diverges from the error-free curve, when video packets are lost, although the highest PSNR degradation is limited to 2dB. Furthermore, the

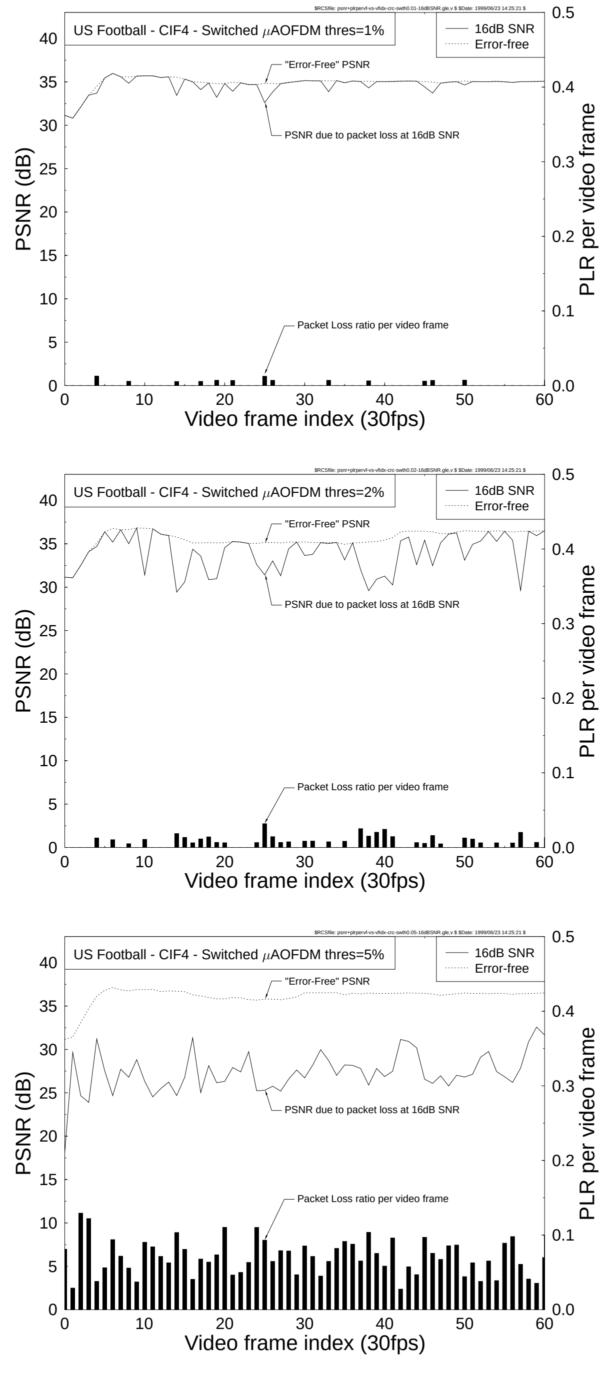


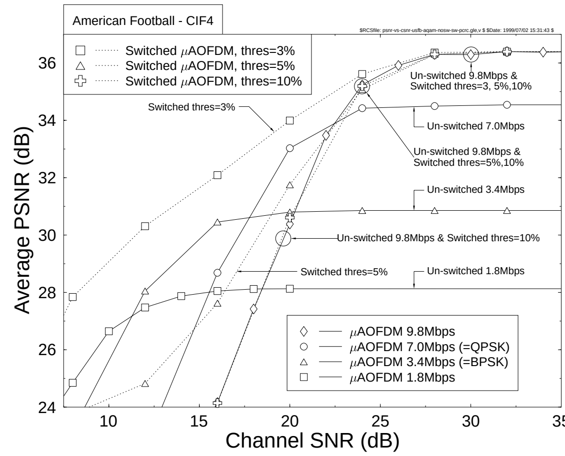
Fig. 10. Video quality and packet loss ratio performance versus video frame index (time) comparison between switched TVTBR-AOFDM transceivers with different BER switching thresholds, at an average of 16dB SNR, using the channel model of Figure 3 at a normalised Doppler frequency of $F_D = 7.41 \times 10^{-2}$.

PSNR curve typically reverts to the error-free PSNR performance curve in the next frame. In this example about 80% of the video frames have no video packet loss. When the BER switching threshold is increased to 2%, as shown in the center graph of Figure 10, the video packet loss ratio has increased, such that now only 41% of video frames have no packet loss. The result of the increased packet loss is a PSNR curve, which diverges from the error-free PSNR performance curve more regularly, with PSNR degradations of upto 7dB. It is worth noting that when there are video frames with no packet losses, the PSNR typically recovers, achieving a similar PSNR performance to the error-free case. When the BER switching threshold was further increased to 3% - which is not shown in the figure - the maximum PSNR degradation increased to 10.5dB, and the number of video frames without packet losses was reduced to 6%.

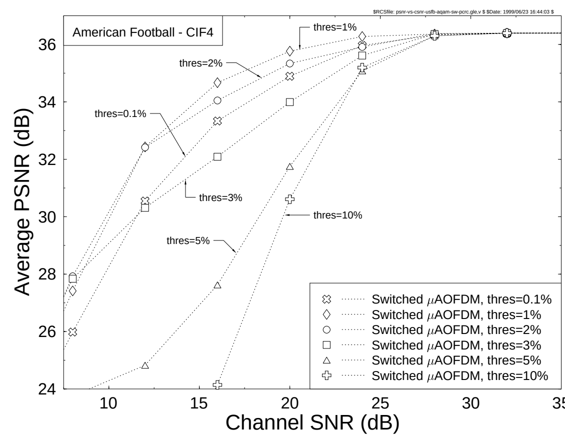
The bottom graph of Figure 10 portrays the PSNR and packet loss performance for a BER switching threshold of 5%. The PSNR degradation in this case ranges from 1.8 to 13dB and all video frames contain at least one lost video packet. Even though the BER=5% switching threshold provides the highest effective throughput bitrate, the associated video quality is poor. The PSNR degradation in most video frames is about 10dB. Clearly, the highest effective throughput bitrate does not guarantee the best video quality. We will now demonstrate that the switching threshold of BER=1% provides the best video quality, when using the average PSNR as our performance metric.

Figure 11(a) compares the average PSNR versus channel SNR performance for a range of switched (TVTBR) and un-switched (CTBR) AOFDM modems. The figure compares the four un-switched, ie. CTBR subband adaptive modems with switching, ie. TVTBR subband adaptive modems, which switch between the four fixed-rate modes, depending on the BER switching threshold. The figure indicates that the switched TVTBR subband adaptive modem having a switching threshold of BER=10% results in similar PSNR performance to the un-switched CTBR 9.8Mbps subband adaptive modem. When the switching threshold is reduced to BER=3%, the switched TVTBR AOFDM modem outperforms all of the un-switched CTBR AOFDM modems. A switching threshold of BER=5% achieves a PSNR performance, which is better than the un-switched 9.8Mbps CTBR AOFDM modem, but worse than that of the un-switched 7.0Mbps modem, at low and medium channel SNRs.

A comparison of the switched TVTBR AOFDM modem employing all six switching thresholds that we have used previously is shown in Figure 11(b). This figure suggests that switching thresholds of BER=0.1, 1 and 2% perform better than the BER=3% threshold, which outperformed all of the un-switched CTBR subband adaptive modems. The best average PSNR performance was achieved by a switching threshold of BER=1%. The more conservative BER=0.1% switching threshold results in a lower PSNR performance, since its throughput bitrate was significantly reduced. Therefore the best tradeoff in terms of PSNR, throughput bitrate and video packet loss ratio was achieved with a switching threshold of about BER=1%.



(a)



(b)

Fig. 11. Average PSNR versus channel SNR performance for switched- and un-switched subband adaptive modems. Figure (a) compares the four un-switched CTBR subband adaptive modems with switched TVTBR subband adaptive modems (using the same four modem modes) for switching thresholds of BER=3, 5 and 10%. Figure (b) compares the switched TVTBR subband adaptive modems for switching thresholds of BER=0.1, 1, 2, 3, 5 and 10%.

V. Conclusions

A range of AOFDM video transceivers have been proposed for robust, flexible and low-delay interactive video telephony. In order to minimize the amount of signalling required we divided the OFDM subcarriers into subbands and controlled the modulation modes on a subband-by-subband basis. The proposed constant target bitrate AOFDM modems provided a lower BER, than the corresponding conventional OFDM modems. The slightly more complex switched TVTBR-AOFDM modems can provide a balanced video quality performance, across a wider range of channel SNRs than the other schemes investigated.

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