I. INTRODUCTION

The wide availability of cell phones and tablet computers has led to an increase in the demand for mobile multimedia applications. There are applications, e.g., news broadcast and video streaming in concerts, in which multiple users attempt to access the same content. When unicast transmission is used, each user must be sent a unique copy of the media. As a consequence, for high user densities the network rapidly runs out of bandwidth. The problem is made even worse since each unicast user also requests the retransmission of any lost data packets via the return channel. While this achieves a reliable link, it prevents the dissemination of media rich content. One solution is to efficiently transmit bandwidth hungry applications such as video over error-prone wireless channels to multiple users in the form of a multicast service. However, robust and reliable data transmission is incompatible with multicast transmissions. Multicast packets are delivered as a simple broadcast service in which Medium Access Control (MAC) layer packet retransmission cannot be implemented. Hence, multicast transmission results in high packet losses. In case of video transmission higher packet loss rate causes serious degradation in the received video quality.

Application layer forward error correction (AL-FEC) based on Raptor codes have been employed in Multimedia Broadcast and Multicast Services (MBMS) [1] to provide reliable multicast/broadcast services. In AL-FEC, redundant data are transmitted along with the source data in order to allow receivers to reconstruct the source file when packet losses occur. AL-FEC reliability comes at the expense of additional bandwidth requirements, hence the amount of redundant data (or code rate) should be determined based on the wireless channel conditions and the selected Modulation and Coding Scheme (MCS) in order to utilise the valuable bandwidth most efficiently. Previous works, such as [2][3][4], address the need for a cross-layer approach where the MCS and Raptor code parameters are jointly selected depending on the channel conditions, in order to optimise the video quality and bandwidth efficiency. However, these works only considered the optimisation of 802.11 Single Input Single Output (SISO) system based on Raptor 10 codes. 802.11n provides high-throughput modes and enhanced bandwidth efficiency via the use of Multiple Input Multiple Output (MIMO) technology [5]. Therefore, in this paper, we consider a cross-layer design based on the latest Raptor Q (RQ) codes for transmitting high data rate video over the MIMO channels in realistic outdoor environments. In channels with high spatial correlation Spatial Multiplexing (SM) [6] results in higher packet loss. To address this issue, we explore a combination of SM multicast transmission with RQ codes. Unlike previous studies where the channel models are simplified, here we use 3D ray-tracing and site specific geographic databases to accurately model the wireless channel. Therefore, the performance of RQ codes is much more realistic.

In the case of MIMO, in addition to MCS mode, MIMO mode (SM and Space Time Block Codes (STBC) [7]) selection is also considered when choosing the optimum transmission parameters. Previous works, e.g., [8][9][10], have proposed different MIMO switching techniques based on capacity, determinant and Demmel condition number in order to increase the spectral efficiency. None of these studies have considered the cross-layer protocol when selecting the best combination of the MCS and MIMO mode. In this work, in addition to the SNR and determinant of the channel matrix [8], the switching algorithm also takes into account RQ code AL-FEC and hence further increases the bandwidth efficiency and service quality.

The remainder of this paper is organized as follows. Section II explains the details of cross-layer simulator. The cross-layer design process is explained in Section III. Simulation results and analysis are provided in Section IV with conclusions presented in Section V.
II. CROSS-LAYER SIMULATOR

A cross-layer simulator has been developed by the authors to evaluate the end-to-end system performance. In order to reduce the computational complexity, the overall system is divided into modular subsystems (video, Raptor, Wi-Fi MAC-PHY layer and channel simulator), each of which is modelled independently.

The video simulator can model the transmission of any H.264 video sequence over the MAC and PHY layers of 802.11n. The video encoder translates video frames into fixed size Network Abstraction Layer Units (NALUs). It is assumed that one NALU is placed into one RTP/UDP/IP packet and also that 802.11 multicast/broadcast packets cannot be fragmented at the MAC layer. Hence, there is a 1:1 mapping between NAL Units and PHY layer Protocol Data Units (PPDU). Therefore, packet error rate (PER) at MAC layer equals to the PER at the application layer.

The Raptor encoder collects the incoming RTP/UDP packets (i.e. source symbols) to construct source blocks each comprising of \( k \) source symbols with \( L_{\text{sym}} \) bytes and then generates a number of repair symbols \( r \) from each block [11]. In this study we consider the latest RQ code since it provides improved performance, coding efficiency and flexibility when compared to the legacy Raptor 10 approach [12]. Since RQ is a systematic code, the first \( k \) encoded symbols are the original symbols. The Raptor code rate is defined as \( CR = \frac{k}{k+r} = \frac{\epsilon}{\epsilon + 1} \). The 802.11n MAC-PHY layer simulator, which is implemented according to standard, models the packet loss pattern for a sequence of NALUs based on the time varying channel created by the ray-tracing model. This process is performed for all MCS/MIMO modes and different Raptor code rates. At the receiver the Raptor decoder waits to collect all the UDP packets belong to a given source block. If the total number of received symbols \( k' \) (source and repair) for a block is \( k' \geq (\epsilon + 1)k \) (for real \( \epsilon > 0 \)), the Raptor decoder is able to decode and all source packets are recovered and delivered to application layer. However, if the decoder fails, only the correctly received source UDP packets are passed up to the application layer. Note that RQ codes are only implemented with SM; for the STBC case RQ codes are disabled. In this paper Raptor codes refer to RQ.

A. System and Channel model

As part of the AIYP (Arkive In Your Pocket) project, this paper contributes to the development of a next generation multimedia broadcast system that will radically enhance the experience of a trip to the Zoo by offering a location dependent Wi-Fi application to hundreds of visitors. The Wi-Fi performance was evaluated in our trial location using a geographic model of Bristol Zoo. Furthermore, we model a user walking along the route shown in Fig. 1. The user was served by two access points (APs), which operate in the 2.4 GHz band and use a transmit power to the antenna port of 20 dBm. In this study the user terminal and AP are assumed to use two antennas and hence support up to 2 spatial streams. A state-of-the-art outdoor 3-D ray-tracer [13] was used to model the time varying MIMO channel matrix \( H \) between the AP and user equipment (UE) in order to replicate the time and space correlated nature of the received signal as the test user moves along the route. The ray-tracer makes use of the physical laws of radiowave propagation, such as reflection, diffraction and scattering and identifies all significant ray paths between the AP and the UE in 3-D space. The ray-tracing database had a resolution of 2 m and included buildings, foliage and terrain data in the Bristol Zoo area. Point-source ray-tracing was conducted from the user to the AP every 6 cm along the route. This provided information on the amplitude, phase, time delay, Angle of Departure (AoD) and Angle of Arrival (AoA) of each multipath component (MPC).

In this paper, we modelled two orthogonally polarised theoretical Hertzian dipoles [14] (i.e. infinitely small electric current sources) in slant orientation at both the UE and the AP. This configuration of two orthogonally polarised antennas was chosen in order to exploit the benefits of the 2x2 MIMO system in a scenario with a strong dominant Line-of-Sight (LoS) path for most of the time. In MIMO communication systems, which take advantage of the multipath propagation, a strong dominant ray component will result in a large spread of the singular values of the channel matrix and hence the MIMO benefits on capacity will be reduced.

B. Link-level abstraction

An Effective SNR Mapping (ESM) PHY abstraction model, known as the Received Bit Mutual Information (RBIR) [15] technique, is used to calculate the PER over time. In the ESM method, a block of OFDM sub-carrier SNRs, which vary severely due to the frequency selective fading, is transformed into a single Effective SNR (ESNR) value. This ESNR value is then used to define the instantaneous PER for any MCS mode using a non-faded PER versus SNR look up table. This table is generated via bit accurate Wi-Fi simulation for an AWGN channel. The MCS modes used in the RBIR simulator are BPSK, QPSK, 16QAM, 64QAM with coding rates of 1/2, 2/3, 3/4 and 5/6 with peak raw data rate of 72.2 Mbps for STBC 2x2 schemes and 144.4Mbps for SM 2x2 scheme for 20 MHz channel bandwidth (with a 400 ns GI) as can be found in [5].
C. Channel quality metric

In a MIMO OFDM system the normalised channel capacity is given as [16]:

\[ C = \frac{1}{N} \sum_{n=1}^{N} \log_2 \left( \det \left( I + \frac{SNR}{N_T} H(n)H(n)^H \right) \right) \]  (1)

where \( N_T, N_R \) are the number of transmit and receive antennas respectively, \((.)^H\) denoted the Hermitian function. Instead of capacity, a simpler channel quality metric which is the determinant of the channel matrix \( H \) (\( \det (H(n)H(n)^H) \)) is used [8].

III. CROSS-LAYER DESIGN

The aim of the cross-layer optimisation process is that for a given mean channel SNR \( \gamma \) and mean \( H \) matrix determinant, select the most appropriate transmission scheme (SM or STBC), MCS mode \( m \) and Raptor code rate \( CR \) (if SM is selected) that provide highest transmission efficiency which is defined by the given mean channel SNR \( \gamma \) and packet size and the application Quality of Service (QoS) requirement. We can formulate the cross-layer optimisation problem as:

\[ T_{SM} = \min_{m, CR} T_{total, SM}(m, CR, k) \]  (2)

\[ T_{STBC} = \min_{m} T_{total, STBC}(m, CR, k) \]  (3)

subject to \( PER_{UDP} \leq PER_{UDP, thr} \)

The total transmission time \( T_{total} \), required to transmit all the UDP packets \( N_{UDP} \) of a video is calculated for different MIMO modes using the equations (4) - (6). It is a function of the MCS mode \( m \), mean channel SNR \( \gamma \), packet size and \( H \) matrix determinant. When SM is used, it also depends on the Raptor code rate \( CR \) and source block length \( k \), and the total transmitted UDP packets depends on the Raptor code rate \( CR \), \( N_{UDP}/CR \). \( T_{DATA} \) is the time required to transmit a PPDU which is the sum of times required to transmit the preamble, \( T_{PRE} \), and the Protocol Service Data Unit (PSDU) \( L_{PSDU} \), and DIFS, SIFS, back-off time \( T_{BO} \). In equation (5), \( N_{SYM} \) is the number of OFDM symbols required for transmission of an \( L_{PSDU} \), the number 2.75 comes from the overhead of service and tail bits, \( m_{STBC} = 2 \) if STBC is used otherwise \( m_{STBC} = 1 \), \( N_{DBPS}(m) \) is the number of data bytes per OFDM symbol for a given MCS mode \( m \). The upper layer headers sizes (RTP/UDP/IP/MAC), PHY layer times and Raptor parameters \((k, L_{SYM})\) are summarised in Table I.

\[ T_{DATA} = DIFS + T_{BO} + T_{PRE} + T_{SYM} \cdot \left[ \frac{T_{SYM} N_{SYM}}{T_{SYM} + T_{SIFS}} \right] + T_{SIFS} \]  (4)

\[ N_{SYM} = m_{STBC} \cdot \left[ \frac{L_{PSDU} + 2.75}{N_{DBPS}(m) m_{STBC}} \right] \]  (5)

\[ T_{total} = \frac{N_{UDP}}{CR} \cdot T_{DATA} \]  (6)

Finally, if \( T_{SM} < T_{STBC}, \) SM is chosen with the optimum MCS mode and code rate pair \((m, CR)\) otherwise, STBC with the optimum MCS mode \( m \) is chosen for the transmission of data.

IV. RESULTS AND ANALYSIS

The performance of multicast video transmission over WLANs is analysed in terms of received UDP PER and transmission efficiency. Firstly, we evaluate the optimum system parameters under different channel conditions. To this end, a constant bitrate video sequence which consists of 1500 UDP packets is transmitted at 4 Mbps. Then, we investigate the benefit of the proposed system in a realistic environment (along the route in Fig. 1).

A. Evaluation of optimum parameters under different MIMO channel conditions

In order to efficiently adapt the system to underlying MIMO channel conditions which is characterised by the mean received SNR and \( H \) matrix determinant, first there is a need to identify the optimum parameters such as MCS/MIMO modes and Raptor code rates for different environments. To this end, we combine the ray data with the 802.11n MAC-PHY layer simulator and calculate the UDP PER for all MCS/MIMO modes and different Raptor code rates in the range from 0.5 to 0.95. Fig. 2 compares the UDP PER performance of MCS modes QPSK 1/2, 16-QAM 1/2 and 64-QAM 2/3 with and without Raptor AL-FEC for SM system under different correlation conditions. Note that we have done simulations for \( H \) matrix determinant range from 0.01 to 2 but here we provide some representative results.

It is well-known that when correlation is high (\( H \) matrix determinant is low (Fig. 2a)), MCS modes require higher SNR to meet the target reliability, which is \( PER_{UDP} \leq 10^{-2} \) in this paper, as compared to the low correlation case (Fig. 2b). It can be seen that with the use of Raptor codes, the required SNR range can be significantly improved. For example, 64-QAM 2/3 provides reliable communication for SNR>24 dB with a \( CR=0.5 \), instead of 33 dB without Raptor codes in Fig. 2a. The improvement depends on the amount of correlation between MIMO channels, i.e., when correlation is low the gain provided by Raptor codes is low compared to the high correlation case. Results also indicated that when correlation is high, even very low CIs fail to deliver error free or quasi-error free data for low UDP PERs. For extensive simulations, we find out that with a \( CR=0.5 \), the highest UDP PER that can be compensated (i.e., the residual UDP PER is \( PER_{UDP} \leq 10^{-2} \) for \( H \) matrix determinant of 0.1, 0.5 and 1 is 0.17, 0.33 and 0.37 respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLCP preamble time, ( T_{PRE} )</td>
<td>40 µs</td>
</tr>
<tr>
<td>Symbol interval, ( T_{SYM} )</td>
<td>4 µs</td>
</tr>
<tr>
<td>Short GI symbol interval, ( T_{SIFS} )</td>
<td>3.6 µs</td>
</tr>
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<td>RTP header</td>
<td>12 bytes</td>
</tr>
<tr>
<td>UDP header</td>
<td>8 bytes</td>
</tr>
<tr>
<td>IP header</td>
<td>20 bytes</td>
</tr>
<tr>
<td>MAC header</td>
<td>36 bytes</td>
</tr>
<tr>
<td>Raptor symbol size, ( L_{SYM} )</td>
<td>1400 bytes</td>
</tr>
<tr>
<td>Source block length, ( k )</td>
<td>200</td>
</tr>
</tbody>
</table>

### Table I: Simulation Parameters
Decoding success of the Raptor codes depends on the symbol error rate encountered in a source block (BLER). In general we observe that in low correlation conditions, the variance of BLERs is low (BLERs close to UDP PER) when compared to the high correlation scenario where we observe longer burst of errors in some source blocks which require very low Raptor code rates to be successfully decoded.

It is clear that in the case of MIMO the optimum parameters not only depend on mean SNR but also depend on the spatial correlation between MIMO channels. Therefore, for given mean SNR and H matrix determinant, we determine the MCS mode and optimum CR pair that provide the lowest total transmission time with the constraint that $PER_{UDP} \leq 10^{-2}$ as explained in Section III. Fig. 3 shows the total transmission time versus SNR for H matrix determinant of 0.5 and Fig. 4 shows the corresponding optimum CRs used to calculate the total number of encoded UDP packets, $N_{UDP}/CR$, for each MCS modes and the optimum CR over all MCS modes.

It can be seen that the use of Raptor codes can deliver quasi-error free data at low SNR values even though the spatial correlation is high. For example, BPSK 1/2 provides reliable communication with a CR of 0.6 at SNR=8 dB, however, without Raptor codes a mean SNR of 16 dB is required. We compare the achievable optimum PHY rates depending on mean SNR and H matrix determinant with and without Raptor codes in Fig. 5. It is clear from the figure that using Raptor AL-FEC enables higher MCS modes to be selected for data transmission. The benefits of Raptor codes are outstanding especially at low SNRs and high correlation conditions at which the legacy system does not provide any service (PHY rate is zero). One can also observe from Fig. 4 that at each MCS mode when SNR increases the CRs also increase (less overhead) due to lower PER as a result the required total number of encoded UDP packets and hence total transmission time decreases. When the MCS mode increases, the optimum code rate increases. The fact that 802.11n has discrete data rates and the ratio between the data rate of consecutive MCS modes decreases as MCS mode index increases. In order to show the trend, Fig. 6 compares the performance of MCS modes for different CRs and MIMO
modes (SM and STBC). Note that $CR=1$ represents the results without Raptor codes. As seen, for higher MCS modes there is little performance difference (gain) that can be exploited by Raptor codes therefore the available $CR$ range is decreased. Furthermore, the results also show that STBC provides higher spectral efficiency than SM with $CR=0.5$ at each MCS mode. Therefore, in the case of MIMO switching the code rate range must be $CR>0.5$.

Next, we compare the performance of MIMO modes under different channel conditions. Fig. 7 shows the optimum MIMO/MCS mode that provide most efficient data transmission for given channel knowledge in terms of mean SNR and $H$ matrix determinant (we only present three values). It can be seen that when the correlation is high (mean $H$ matrix determinant of 0.1 and 0.5), STBC is selected until the SNR values that enable higher MCS modes to be implemented in SM, e.g., 36 dB and 28 dB for the mean $H$ matrix determinant of 0.1 and 0.5 respectively. However, when correlation decreases, e.g., mean $H$ matrix determinant 1, the use of Raptor codes allows lower MCS modes such as QPSK 3/4 and 16-QAM 1/2 in SM scheme to be selected. Moreover, as mean $H$ matrix determinant is equal or higher than 2, STBC is only selected at SNR $\leq 2$ dB, otherwise SM is selected. The optimum CRs depending on the correlations can be seen in Fig. 8. It is clear that when the correlation decreases the required CR increases as explained before.

Finally, we evaluate the proposed system in a realistic environment. To this end, a constant bitrate video sequence is transmitted at 4 Mbps. The MAC-PHY layer simulator is used to model the packets loss patterns through the route for different MCS modes, MIMO schemes and Raptor code rates. Since the channel changes over time we evaluate the link adaptation parameters over half second time periods (time slots). While Fig. 9 show the SNR and $H$ matrix determinant, Fig. 10 shows the achievable PHY rates through the route for SM with and without Raptor codes and STBC. It is observed that in areas with low SNR and high spatial correlation (low $H$ matrix determinant) STBC shows better performance than SM. In these locations, SM fails to provide service without Raptor codes (PHY rate is zero). However, with the use of Raptor codes the SM performance can be significantly improved. The SM system never fails and provides service all over the test route, even in very challenging locations with low SNR and high correlation since Raptor code can generate as many repair symbols as required in order to compensate the PER. When channel conditions are good, SM can still make use of higher throughput MCS modes and increase the transmission efficiency unlike STBC which provides limited throughput.

The optimum MIMO/MCS mode through the route selected with the use of cross-layer optimisation approach can be seen in Fig. 11. It should be noted that in Fig. 10 in some locations SM with Raptor shows higher PHY rates than STBC but in Fig. 11 STBC is chosen for these locations. This is because Raptor code overhead increases the total transmission time and hence results in reduced transmission efficiency. As seen from the figure, the adaptive MIMO mode switching exploits the benefits of both SM and STBC. In general, STBC performance depends on the SNR, whereas SM performance depends on both the SNR and the spatial correlation. In the case of MIMO switching, SM takes advantages of Raptor codes, especially when correlation is low, and provides higher transmission efficiency, i.e., the overall channel occupancy time is less than the system without Raptor codes.
of higher throughput MCS modes when channel conditions are good therefore increases the overall transmission efficiency. In the case of MIMO switching, when the spatial correlation is high SM requires higher repair symbols to provide reliability this results in reduced transmission efficiency. Therefore in these locations STBC provides better performance. SM shows better performance when correlation is low.

In conclusion, results clearly show that Raptor code AL-FEC can be used to increase the reliability and transmission efficiency of the systems, if MIMO channels experience low spatial correlations.

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REFERENCES

[1] 3GPP TS 26.346 V8.0.0 (2008-10) universal mobile telecommunications system (UMTS); multimedia broadcast/multicast service (MBMS); Protocols and codecs, 2008.