Abstract—This paper exploits Application Layer Forward Error Correction (AL-FEC) based on Raptor codes to achieve for reliable video multicast over 802.11n multiple-input multiple-output (MIMO) channels. The system performance and cross-layer optimisation parameters are analysed for spatial multiplexing (SM) waveforms under different channel conditions and quality of service requirements. Results show that the transmission efficiency and reliability of the SM system can be significantly improved when AL-FEC codes are employed. Improvements of up to 8 dB in terms of SNR were observed depending on the channel condition, chosen modulation and coding scheme and Raptor code rate. Moreover, at low SNR and for channels with low spatial correlation, the performance of SM with AL-FEC code shows better performance than that of STBC.

Keywords— Raptor codes; MIMO; spatial multiplexing; space-time block coding; reliable multicast; IEEE 802.11 WLAN

I. INTRODUCTION

The wide availability of cell phones and tablet computers has led to an increase in the demand for mobile multimedia applications. Unicast protocols struggle to meet these demands since radio and network resources are shared between users. 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 retransmission cannot be implemented. Hence, multicast transmission results in high packet loss rates. 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. AL-FEC reliability comes at the expense of additional bandwidth requirements, hence the Raptor overheads (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 bandwidth most efficiently. Although there are previous works on Raptor codes, there are few papers that consider Raptor code performance in combination with WLANs and even fewer that consider cross-layer optimisation where the MCS mode and Raptor code parameters are jointly selected depending on the channel conditions [2][3][4]. Furthermore, all of these studies have only considered cross-layer optimisations for a Single Input Single Output (SISO) system. 802.11n provides high-throughput modes and enhanced bandwidth efficiency via the use of Multiple Input Multiple Output (MIMO) technology [5]. Therefore, in this work we evaluate the performance of Raptor codes with MIMO based WLAN waveforms to transmit high data rate video to users in realistic outdoor environments which has not been considered before. Spatial Multiplexing (SM) [6] MIMO technique provides higher data rates by splitting the incoming data stream into independent sub-streams and then transmitting these streams via individual antennas. In channels with high spatial correlation SM results in high packet loss. To address this issue we explore combination of SM multicast transmissions with Raptor codes. Furthermore, we compare the combined SM and Raptor code scheme with a space-time block coding (STBC) MIMO technique [7] which is already a reliable transmission schemes therefore we do not consider Raptor codes in this system. One of the main contributions of this work is to use a detailed cross-layer simulator and accurately model the wireless channels using a 3D ray-tracer since the simplified statistical channel models and/or random packet loss assumptions lead to inaccurate estimation of the performance of Raptor codes as this is the case in many publications, e.g. [2][3].

The remainder of this paper is organized as follows. Section II explains the details of cross-layer simulation. Results and analysis are provided in Section III with conclusions presented in Section IV.

II. CROSS-LAYER SIMULATION

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).

The Raptor encoder collects the incoming RTP/UDP packets (i.e., source symbols) to construct source blocks each comprising of \( k \) source symbols with \( L_{sym} \) bytes and then generates a number of repair symbols \( r \) from each block [8]. 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 [9]. Since RQ is a systematic code, the first \( k \) encoded symbols are the original symbols. The Raptor code rate is defined as \( CR = \frac{k}{k+r} = \frac{e}{n} \). The 802.11n MAC-PHY layer simulator which is implemented according to standard [5] models the packet loss pattern for a sequence of NALUs based on the time varying channel created by the ray-tracer. This process is performed for all MCS/MIMO modes and different Raptor code rates. Note that at the MAC layer Distributed Coordination Function (DCF) is assumed. DCF transmission time for high throughput mixed format packet can be found in [5]. 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 (source and repair) for a block is \( k' \geq (e+1)k \) (for real \( e > 0 \)), 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 refers 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 [10] was used to model the time varying MIMO channel matrix \( \mathbf{H} \) 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 shown in Fig. 1. 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). The complex gain of each MPC was adjusted according to each transmitting/receiving antenna electric far-field pattern response for the corresponding AoD/AoA and polarisation. The double-directional time-variant channel impulse response \( h_{ij} \) between the transmit antenna \( j \) and the receive antenna \( i \) was calculated by equations (1) and (2) [11]:

\[
h_{ij}(t, \tau, \Omega_{\text{AoD}}, \Omega_{\text{AoA}}) = \sum_{l=1}^{L} h_{ij,l}(t, \tau, \Omega_{\text{AoD}}, \Omega_{\text{AoA}}) = \sum_{l=1}^{L} \mathbf{E}_{ij,l}(\tau) \delta(\tau - \tau_{l}) \delta(\Omega_{\text{AoD}} - \Omega_{\text{AoD,l}}) \delta(\Omega_{\text{AoA}} - \Omega_{\text{AoA,l}})
\]

where,

\[
\mathbf{E}_{ij,l} = \left[ \begin{array}{c} E_{X,l}^{V} \\ E_{X,l}^{H} \end{array} \right]^T = \left[ \begin{array}{c} a_{l}^{YY} e^{j\psi_{l}^{YY}} \\ a_{l}^{YH} e^{j\psi_{l}^{YH}} \end{array} \right] \left[ \begin{array}{c} E_{RX,l}^{V} \\ E_{RX,l}^{H} \end{array} \right] e^{j2\pi f_{c} t}
\]

\[
\delta(\cdot) \text{ is the Dirac delta function, } [\cdot]^T \text{ is the transpose of a matrix, } \tau \text{ is the variable of time, } \tau_{l} \text{ is the variable of time-of-flight of a ray, } L \text{ is the total number of MPCs, with a double-directional time-variant channel impulse response } h_{ij,l}(t, \tau, \Omega_{\text{AoD}}, \Omega_{\text{AoA}}) \text{ for the } l^{th} \text{ MPC, and } \Omega_{\text{AoD}}, \Omega_{\text{AoA}} \text{ represents the departure/arrival solid angle. The } l^{th} \text{ MPC has a complex amplitude } a_{l}^{XY} e^{j\psi_{l}^{XY}} \text{ (2x2 matrix for all four polarisation combinations), a time-of-flight } \tau_{l}, \text{ and departure/arrival solid angles } \Omega_{\text{AoD,l}}, \Omega_{\text{AoA,l}}. \text{ The Doppler frequency shift } f_{l} \text{ of the } l^{th} \text{ MPC is given by equation (3) [12]}:
\]

\[
f_{l} = \frac{|v| \cos(\omega_{\text{AoA,l}} - \omega_{\text{AoA}}) \cos(\zeta_{\text{AoA,l}} - \zeta_{\text{AoA}})}{\lambda}
\]

Fig. 1. Route modelled in the Bristol Zoo colour-coded according to the received SNR at the user. AP locations are also marked.
wavelength. $E_{V,H}^{ij}$ and $E_{R,H}^{ij}$ represent the vertical/horizontal polarisation component of the complex electric far-field radiation pattern of the transmit antenna $i$ and the receive antenna $j$ respectively. In this paper, we modelled two orthogonally polarised theoretical Hertzian dipoles [13] (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

Performing bit accurate PHY simulations for large numbers of users, as well as the full range of modulation and coding schemes (MCS), is computationally prohibitive. Therefore, an Effective SNR Mapping (ESM) PHY abstraction model, known as the Received Bit Mutual Information (RBIR) [14] technique, is used to calculate the packet error rate (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 using (4).

$$ESNR = \Phi_{m}^{-1}\left(\frac{1}{N_{m}N_{s}}\sum_{n=1}^{N_{s}}\sum_{k=1}^{N_{m}}\Phi(SNR_{n,k})\right) \tag{4}$$

In (4), $SNR_{n,k}$ represents the post-processing signal to noise ratio (SNR) for the $k$th spatial stream of the $n$th sub-carrier and $m$ represents the modulation order. $N$ represents the number of sub-carriers in the block, $N_{s}$ is the maximum number of spatial streams, and $\Phi(\bullet)$ is an invertible function. The Mutual Information (MI) ESM approach is used in this paper that defines $\Phi(\bullet)$ as the Symbol Information (SI) as given in equation (5),

$$SI(Y,m) = E_{xy}\left\{\log_{2}\frac{P(Y|X,Y)}{\sum_{X}\sum_{Y}P(X,Y)}\right\} \tag{5}$$

where $Y$ denotes the received symbol with input SNR equal to $\gamma$ and $P(Y|X,Y)$ is the AWGN channel transition probability density conditioned on the noise-free transmit symbol $X$.

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 ESM PHY abstraction method is described in greater detail in [14]. The transmission modes for an 802.11n 20 MHz channel profile (with a 400 ns GI) [5] are used in the RBIR simulator can be seen in Table I for both SM and STBC schemes.

C. Performance evaluation

A constant bit rate video sequence is transmitted at 4 Mbps. The PHY-MAC 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 parameters over one second time periods (time slots) in order to present how different channel conditions affect the choices of system parameters, e.g. MCS mode and Raptor code rate. The MIMO channel is characterised by the received SNR and $H$ matrix determinant as in [15]. In the case of STBC and SM without Raptor codes, the most appropriate MCS mode for the channel conditions is selected from the MCS mode that provide a UDP PER less than a target UDP PER (e.g. 1%), which is defined according to the application’s QoS requirement, with the highest peak rate, $R = (1 - PER)D$, where $R$ is the peak rate and $D$ is the link speed. In the case of SM with Raptor codes, the optimum MCS mode was selected taking into account the Raptor code rate (i.e. Raptor aware link adaption). Again MCS modes and Raptor code rates are chosen such that they provide less than a target UDP PER, then the peak rate is calculated for these MCS modes and code rate pairs such as $R = (1 - PER)D.CR$. The pair with the highest peak rate is chosen for transmission.

III. SIMULATION RESULTS AND ANALYSIS

In this section, the performances of the MIMO transmission schemes are presented in terms of achievable peak rate and UDP PER at the application layer. The system performance is evaluated along the route with different channel conditions. Combining the ray data with the 802.11n PHY-MAC simulator, the UDP PER for SM with/without Raptor codes and STBC is calculated. Note that for all simulations the symbol/packet size is 1400B and Raptor source block length $k$ is 200. An example of the system performance in terms of mean SNR versus UDP PER for the transmission of 1500 UDP packets with different mean $H$ matrix determinants as shown in Fig. 2. It can be seen that when the spatial correlation is high in Fig. 2a ($H$ matrix determinant is low) the performance of the SM system degrades seriously compared to STBC, i.e. SM requires around 20 dB more SNR. However, the SM performance is improved as the spatial correlation reduces ($H$ matrix determinant increases) as shown in Fig. 2b in which SM requires around 10 dB more SNR compared to the STBC. Similar results can be found in [15].

Next we perform simulations on Raptor code enabled video multicast transmission. Our main interest is to implement Raptor codes in the SM system and investigate the system performance under different channel conditions. Again we transmit 1500 UDP packets but this time packets are encoded

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>Data rate (Mbps)</th>
<th>20 MHz channel, 400 ns GI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>7.2</td>
<td>148</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>1/2</td>
<td>14.4</td>
<td>28.9</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>3/4</td>
<td>21.7</td>
<td>43.3</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>1/2</td>
<td>28.9</td>
<td>57.8</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>3/4</td>
<td>43.3</td>
<td>86.7</td>
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<tr>
<td>6</td>
<td>64-QAM</td>
<td>2/3</td>
<td>57.8</td>
<td>115.6</td>
</tr>
<tr>
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<td>64-QAM</td>
<td>3/4</td>
<td>65</td>
<td>130</td>
</tr>
<tr>
<td>8</td>
<td>64-QAM</td>
<td>5/6</td>
<td>72.2</td>
<td>144.4</td>
</tr>
</tbody>
</table>
with different Raptor code rates, $0.5 \leq CR \leq 0.95$. When Raptor codes are employed, the UDP PER is calculated after Raptor decoding. Fig. 3 compares the performance of MCS modes QPSK 1/2, 16-QAM 1/2 and 64-QAM 2/3 before and after Raptor decoding for specific channel scenarios which are defined by the mean $H$ matrix determinant. It can be seen that depending on the MCS, $H$ matrix determinant and CR there would be as much as 8 dB improvement in the required SNR. For example, in Fig. 3a QPSK 1/2 requires SNR>28 dB in order to provide error-free data, however, when Raptor codes are implemented with a code rate of 0.5 the required SNR is SNR>20 dB. This enables either using higher MCS mode for the transmission of data when channel condition is good and/or extending coverage area when channel condition is bad. It is also observed that when correlation is high (Fig. 3a) even very low CRs fail to deliver error-free or quasi error-free data to application. For example, in Fig. 3a, QPSK 1/2 provides a PER of 0.3 at SNR=20 dB and fails to deliver error-free data even if CR=0.5 is used. When correlation is low (Fig. 3b) a CR of 0.5 can provide error-free transmission for QPSK 1/2 with a PER of 0.37 at SNR=8 dB. This is because the decoding success of Raptor codes depend on the symbol error rate in a source block and even if a single block is not decoded successfully this results in very high UDP PER. In general when correlation is high, the probability of observing longer burst of errors in a source block is increased.

Based on the methodology explained in Section II C, we evaluate the performance of the proposed system along the whole route in Fig. 1. The received SNR and $H$ matrix determinant (calculated from the ray-traced channels) can be seen in Fig. 4. The corresponding MCS modes using the application layer PER constraint of $\text{PER} < 1\%$ are shown in Fig. 5 for the SM system with and without raptor codes. Note that Mode 0 implies that no MCS mode achieves the target PER (outage). It can be seen that in most of the areas with high spatial correlation (low $H$ matrix determinant) and low SNR, SM without Raptor codes fails to provide service. However, with the use of Raptor codes 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 the Raptor code can generate as many repair symbols as required. Fig. 6 shows the required Raptor code rates under different channel conditions. It is also observed that Raptor codes enable higher MCS modes to be selected for transmission especially when correlation is low and hence increase the transmission efficiency.

Next, we compare the achievable peak rate for SM with/without Raptor codes and STBC. Fig. 7 shows the results. Note that using lower Raptor codes results in lower throughput since more redundant packets are transmitted. As STBC is a reliable scheme we do not implement Raptor codes in this case. It can be seen that when spatial correlation is low the
performance of the SM with Raptor code is better than that of STBC at low SNR. However, when spatial correlation is high, even if then SNR is high (e.g. between time slots of 420-500), the performance is lower than STBC since STBC performance strongly depends on the SNR that allows a higher MCS mode to be used, whereas SM performance depends on both the SNR and the spatial correlation.

IV. CONCLUSIONS

In this paper we have investigated the benefits of Raptor codes for transmitting high data rate video over 802.11n MIMO channels in a realistic outdoor environment. Results indicate that using Raptor codes in the SM system enables even higher MCS modes to be used when correlation is low (good channel conditions) and allows a certain level of service when correlation is high (bad channel conditions). It is also observed that the required SNR can be improved by up to 8 dB depending on the channel conditions and Raptor code rate. Furthermore at low SNR and correlation, the performance of SM with Raptor codes outperforms STBC.

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Fig. 4. Received SNR and H matrix determinant through the route.

Fig. 5. SM mode chosen with/without Raptor code, UDP PER <1%, k=200.

Fig. 6. Required Raptor code rate for UDP PER <1%, k=200.

Fig. 7. Comparison of achievable peak rate, UDP PER <1%, k=200.