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Abstract—This paper focuses on the problem of ensuring quality of service (QoS) to 4G network users. An adaptive cross-layer (ACL) strategy, that jointly optimizes the parameters of physical (PHY) and medium access control (MAC) layers using queueing theory, is proposed and applied to mobile user communications in an OFDM-based wireless network. PHY and MAC layers are referring to IEEE 802.16 standard, supporting, respectively, different modulations and the automatic repeat request (ARQ) protocol. PHY and MAC layer parameters are here optimally combined by ACL strategy to meet the QoS requirements.

The main contribution of the paper is the evaluation of the impact of mobility on ACL strategy performance, by using an accurate channel model that accounts for shadowing effects. The simulation results show that the ACL strategy outperforms non-adaptive or single-layer strategies, in terms of bandwidth savings. Also, ACL strategy is able to guarantee the requested QoS in the different mobility scenarios with different degrees of performance.

I. INTRODUCTION

Fourth generation wireless networks are going to offer high transmission rates to stationary and mobile users and to support the convergence of data, voice, and video transmissions. Such convergence imposes strict requirements on the quality of service (QoS) that must be ensured to users’ transmission. QoS guarantees are extremely difficult to maintain in wireless networks, especially due to the intermittent quality degradation that radio channel may experience. Degradations and fluctuations of the channel quality can be caused by various impairments and are further exacerbated by high user mobility and high data rates. In order to achieve the requested QoS, strategies that counteract the channel quality variations in an adaptive way are, thus, necessary.

Adaptive strategies for guaranteeing QoS may exploit the various degrees of flexibility and redundancy that are offered by the different layers of fourth generation (4G) wireless network. It is well-known that the choice of the layer at which the adaptive strategy is implemented affects the overall performance of the wireless network. In particular, strategies implemented at the upper layers (e.g., IP layer) could be slowly counteract the channel variations. In addition, if different disjoint strategies are implemented at the different layers, lower layers (e.g., PHY layer) may tend to promptly under or over-compensate the channel quality degradation and, thus, the upper layer may strive to achieve the QoS requirements. Therefore, the adaptive strategy must feature a cross-layer approach to optimally achieve the QoS requirements and a prompt adaptivity to compensate channel quality variations.

A number of previous work considered cross-layer strategies suitable for 4G networks (e.g., [1], [2]). The performance of the proposed solutions has been mainly evaluated for stationary users. The effects of slowly varying channel quality information (CQI) on ARQ protocol are evaluated in [3]. In such paper, channel state information is derived as a ratio between number of transmitted bits and bit errors over a long observation period. The estimation is computed on a sliding windows and four simple adaptation algorithms are provided. These strategies can react only after a certain number of errors, thus with a delay that is not tolerable by real time traffic.

A more accurate channel model that accounts for CQI variations is considered in [1], [2], [4], [5]. The model is based on a finite state Markov chain (FSMC) that alternates good and bad channel quality states, according to simulation parameters. Transition probabilities and state holding times are inferred from statistical measurements of the wireless channel and lacks of a proper model for the user mobility inside a wireless network cell.

This paper proposes an adaptive cross-layer (ACL) strategy that jointly and promptly optimizes the PHY and MAC parameters. The objective of ACL strategy is two-fold, i.e., to meet QoS requirements and to allocate the minimum amount of bandwidth necessary for transmissions. The proposed adaptive strategy is applied to a 4G network based on an orthogonal frequency division modulation (OFDM) PHY layer. System parameters are set according to IEEE 802.16 standard [6], [7]. PHY and MAC layer of IEEE 802.16 support, respectively, different modulation profiles and an automatic repeat request (ARQ) protocol, that are optimally combined by the ACL strategy. The optimization is based on the analytical evaluation of the QoS performance in terms of packet loss and expected delay, derived using queueing theory.

The contribution of the paper is the application of the ACL strategy to a mobile user scenario, in which the transmission channel is affected by both fast and slow fading. The slow fading inter-frame process is originated by the shadowing due to buildings or obstacles, encountered along the mobile user trajectories. The performance of the ACL strategy is
evaluated assuming perfect and immediate knowledge of CQI. Simulation results assess the adaptivity and the optimality of the ACL strategy under different user mobility scenarios and quantify the impact of user mobility on QoS.

II. WIRELESS NETWORK ARCHITECTURE

The ACL strategy is tested over the radio link between the base station (BS) and a single mobile station (MS). BS and MS communicates using IEEE 802.16 protocols, operating in point-to-multipoint mode.

IEEE 802.16 is a connection-oriented protocol and transmissions are time-division multiplexed. In each time frame, the BS schedules the transmissions and indicates the downlink and uplink bandwidth allocation in a map along with the PHY layer parameters. Data packets, i.e., MAC protocol data unit (PDU), are transmitted during the scheduled time allocation.

Without loss of generality, a single connection, referred to as service flow, is established on the radio link from BS to MS. The following assumptions are made on the derivation of the cross-layer optimization scheme.

A. PHY and MAC Layer Assumptions

It is assumed that the transmitted power at BS is kept constant. Channel is affected by fast and slow fading as described in Sec. IV-A. The BS has the perfect and immediate knowledge of the CQI. The service flow is an Unsolicited Grant Service (UGS) type. The PDU packets of UGS have fixed size and are assumed to be periodically issued (e.g., UGS supporting voice traffic streams). Issued PDUs are stored in a buffer with unlimited capacity. In each time frame, the bandwidth required for PDU transmission is dynamically and optimally allocated upon ACL strategy computation.

III. ACL STRATEGY

The main objective of the cross-layer optimization is to minimize the amount of bandwidth necessary for transmitting the service flow PDUs, while ensuring the requested QoS. The bandwidth required to transmit a single PDU is defined as the bandwidth (e.g., allocated time) for the first time transmission of the PDU and for the subsequent retransmission of the same PDU, until either the PDU is successfully received or the maximum number of retransmissions is reached.

QoS requirements include maximum PDU loss rate, $L_{\text{max}}$, and may include a set of other QoS requirements (such as delay and jitter), $Q$.

To minimize the bandwidth while ensuring QoS requirements, the PHY and MAC layer parameters are optimally and jointly decided. The PHY layer parameters (e.g., modulation order, code type, and rate) allows to define the PHY profile to select. The MAC layer parameters include whether ARQ protocol is required, and if so the maximum number of times, $K$, the transmission of the same PDU should be attempted, before dropping the PDU.

Let $S$ be the set containing the spectral efficiency of each PHY profile. Let $\lambda$ be the expected arrival rate of PDUs. Let $P_i$ be the expected probability that a fixed-size PDU, transmitted using PHY profile $i$, is received incorrectly, for a given CQI.

Under the assumption of unlimited buffer capacity, PDU losses occur only when the maximum number of transmission attempts (i.e., $K$) is reached. Thus, let $f(L_{\text{max}}, P_i)$ be the function that optimally selects the MAC parameter $K$ to meet $L_{\text{max}}$ values. Also, assume to know the set of functions $g_j(K, \lambda, P_i)$ that evaluate each QoS metric $j$.

The cross-layer optimization works as follows. The various PHY profiles are considered, starting from those at maximum spectral efficiency, i.e., $\xi = \max_s S[s]$. Among the PHY profiles having the same spectral efficiency, the PHY profile at minimum PDU error rate is selected, i.e., $\rho = \min_{i, S[i]=\xi} P_i$. Then, the optimal number of transmission attempts, $K_{\text{opt}}$, for the given value of $\rho$ and $L_{\text{max}}$ can be derived as

$$K_{\text{opt}} = f(L_{\text{max}}, \rho). \quad (1)$$

If constraint $g_j(K_{\text{opt}}; \lambda, \rho) < Q[j]$ holds for each QoS metric $j$, then the optimum MAC parameter $K_{\text{opt}}$ and PHY profile $s_{\text{opt}} = s$ are found. Otherwise, the QoS for the other PHY burst options at the same spectral efficiency $\xi$ (if any) is evaluated. If QoS is not met, the other PHY profile options at decreasing spectral efficiency are evaluated.

Such cross-layer strategy is performed each time the CQI deviates significantly. A flow-chart of the strategy is sketched in Fig. 1. Notice that the PHY profile at maximum spectral efficiency is selected when QoS requirements are met. Also, for the same spectral efficiency, PHY profile with the best performance in terms of PDU error rate is selected. A derivation of functions $f(.)$ and $g_j(.)$ is presented next.

A. Analytical Evaluation of QoS Performance

The above presented ACL strategy is applied to the case in which the the QoS requirements are given in terms of maximum PDU loss rate, $L_{\text{max}}$, and expected PDU delay, $D_{\text{max}}$. The estimation of PDU loss rate, $L$, and the expected
PDU delay, $\bar{D}$, are analytically derived in this section using a queueing model based on the following assumptions.

Realizations of the statistical process representing the BS-MS channel behavior during a time frame are assumed to be independent on a time frame basis, i.e., fast fading is assumed to be block fading. BS can schedule a single PDU per time frame. Fragmentation or packing of PDU is not considered. ARQ acknowledgments are promptly received. Therefore, the ARQ protocol is based on stop-and-wait mechanism, with up to $K$ transmissions of the same PDU, as shown in Fig. 2.

![Figure 2. Considered stop-and-wait ARQ protocol](image)

Under the above mentioned assumptions, the performance of stop-and-wait protocol can be evaluated using a discrete time queuing model with Bernoulli arrivals at rate $\lambda$ of stop-and-wait protocol can be evaluated using a discrete time queuing model with Bernoulli arrivals at rate $\lambda$ and an expected service time ($X$) whose first moment ($\bar{X}$) and second moment ($\bar{X}^2$) are as follows:

$$\bar{X} = T_f \left( \sum_{h=1}^{K} h^2 P_{h}^{h-1} (1 - P_{i}) + K \cdot P_{i}^K \right)$$

$$\bar{X}^2 = \left( \sum_{h=1}^{K} h^2 P_{h}^{h-1} (1 - P_{i}) + K^2 \cdot P_{i}^K \right)$$

where $T_f$ is the frame duration.

The expected delay experienced by correctly received PDUs is minimal. The QoS metric function concerning the expected delay is $f(L_{max}, P_{i}) = \bar{D}$ (Eq. (4)).

Finally, the expected amount of bandwidth necessary in each time frame for supporting the service flow is equal to $\lambda \cdot \bar{X}$ times the bandwidth required for transmitting one PDU.

### IV. PERFORMANCE EVALUATION

In this section, after a detailed description of the channel model for mobile users and of the system parameters, the performance of the proposed ACL strategy is evaluated in different mobility scenarios. The ACL strategy is compared against two strategies. First, a single-layer (SL) strategy optimizes the MAC parameters only, according to the updated CQI, when PHY parameters are fixed and given. Second, a cross-layer (CL) strategy, that is not aware of CQI variations over time, optimizes jointly PHY and MAC parameters, according to the average average channel quality (i.e., signal-to-noise ratio).

#### A. Channel Model

The following channel model is used to account for mobility. The MS is assumed to move inside a network cell, along a circular path centered at the BS. The channel model for the MS is based on ITU vehicular type A model [9]. MS mobility induces shadowing effects, that make the received average signal-to-noise, $\Gamma$, fluctuate according to a log-normal distribution. The coherence time of such fluctuations is larger than fast fading coherence time. Path loss variations are neglected as the changes are slower than shadowing, especially in urban mobility scenario.

For comparison purposes, a frequency flat fading model, suitable for line of sight transmissions without Doppler effects, is considered. In the line of sight case, power of the delayed multipath replicas is very low and no frequency selectivity is appreciated.

#### B. System Parameters

The performance of the proposed cross-layer approach is evaluated for an OFDM-based PHY layer, according to the parameters indicated in Table I. Parameters are defined according to IEEE 802.16 [6] standard. PHY profiles consist of three different types of modulation, i.e., 4-QAM, 16-QAM, and 64-QAM, applied to uncoded data. Carrier frequency is centered at 3.5 GHz and the wavelength is 8.6 cm. MS speed is 50 Km/h, which leads to a Doppler frequency of about 160 Hz for the specified carrier frequency. Shadowing is supposed to have a spatial coherence of 20 wavelengths. For the considered MS speed and time frame duration, shadowing causes a log-normal $\Gamma$ deviation every 120 ms or 24 time frames. It is assumed that only 2 dB variations of $\Gamma$ are detected (i.e., the log-normal distribution is quantized with 2 dB step over a given $\Gamma$ range). The standard deviation of $\Gamma$ depends on the mobility scenario. Shadowing parameters for the different mobility scenarios are selected according to [10] and reported in Table II.

Upon detection of a channel quality variation, BS promptly performs the cross-layer optimization, presented in Sec. III, and schedule PDU transmissions according to the computed MAC and PHY parameters. Size of PDU packets, including
MAC header and CRC, is fixed to 288 bytes, i.e., 1 (2 or 3) OFDM symbol(s) at 64-QAM (16 or 4 QAM).

Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Data subcarriers</td>
<td>384</td>
</tr>
<tr>
<td>FFT size</td>
<td>512</td>
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<tr>
<td>Subcarrier freq. separation</td>
<td>31.25 KHz</td>
</tr>
<tr>
<td>OFDM symbols in frame</td>
<td>48</td>
</tr>
<tr>
<td>Frame duration ($T_f$)</td>
<td>5 ms</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>102.86 $\mu s$</td>
</tr>
<tr>
<td>Useful Symbol duration</td>
<td>91.43 $\mu s$</td>
</tr>
<tr>
<td>Cyclic Prefix Ratio</td>
<td>1/8</td>
</tr>
</tbody>
</table>

Table II

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Log-normal deviation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Macro Cell</td>
<td>2.3 dB</td>
</tr>
<tr>
<td>LOS fixed station</td>
<td>3.4 dB</td>
</tr>
<tr>
<td>Urban Macro Cell</td>
<td>8.0 dB</td>
</tr>
<tr>
<td>Indoor small office</td>
<td>12 dB</td>
</tr>
</tbody>
</table>

C. Numerical Results

Simulation results of the ACL strategy performance are presented next. Unless otherwise indicated, the ITU vehicular A channel model with log-normal deviation $\sigma = 2.3$ dB and $\Gamma$ range in [26-40] dB is used. QoS requirements to be met for any value of $\Gamma$ in the range: $L_{\text{max}} = 10^{-4}$ and $\overline{D}_{\text{max}} = 25$ ms. PDU arrival rate is $\lambda = 0.1$ PDUs per time frame. In the simulation, retransmissions of the same PDU use the same MAC and PHY parameters computed for the first transmission.

![Figure 3](image)

Figure 3. ITU vehicular A channel: percentage of bandwidth saving vs. $\Gamma$, for ACL and SL strategies, $\sigma = 0$

Fig. 3 plots the percentage of bandwidth saved for transmitting PDUs of a single service flow (with QoS requirements) when bandwidth is dynamically allocated, instead of a fixed bandwidth allocation of 3 OFDM symbols per time frame. Dynamic bandwidth allocation is achieved using ACL strategy or an adaptive MAC (SL) strategy that optimizes MAC parameter $K$ for a given modulation. Results are shown for different values of $\Gamma$, when $\sigma = 0$. In the figure, the curves are obtained using the queuing model, while the points with the error bars indicate the simulation results. Notice that at low values of $\Gamma$ the modulations at higher spectral efficiency are unable to meet QoS requirements. The plot shows the perfect matching between theoretical results and simulation results and the optimality of ACL approach. Moreover, the results quantify the bandwidth savings achieved by strategies with dynamic bandwidth allocation. Also, the results clearly indicate the best performance of the cross-layer strategy (i.e., ACL) with respect to a single-layer strategy (i.e., SL) in terms of both bandwidth savings (for a given $\Gamma$) and wider $\Gamma$ range over which QoS can be guaranteed.

![Figure 4](image)

Figure 4. ITU vehicular A channel: overall number of OFDM symbols used vs. time, for different values of $\sigma$

![Figure 5](image)

Figure 5. ITU vehicular A channel: $\overline{D}$ vs. time, for different QoS requirements of $\overline{D}_{\text{max}}, L_{\text{max}} = 10^{-4}$

Fig. 5 plots the expected delay, $\overline{D}$, computed from time instant at 0 s, versus time, for different requirements of $\overline{D}_{\text{max}}$. Results show that the QoS is met even for the most stringent $\overline{D}_{\text{max}}$ requirements and that $\overline{D}$ is not significantly affected by channel quality fluctuations. The gap between the curves of ACL and CL strategy indicates the amount of bandwidth (in number of OFDM symbols) saved thanks to the adaptive approach. For higher values of $\sigma$ (e.g., user in office), a higher amount of bandwidth is required, because there is a higher probability that the channel quality degrades and thus lower spectral efficiency modulations must be selected.
It is interesting to compare the performance of Fig. 5 against the value of $\overline{D}$ achieved in a flat fading channel, as shown in Fig. 6. The comparison shows that user terminal mobility cause wider fluctuations in the MAC layer performance. Note that the performance of flat fading channel are achieved on a wider $\Gamma$ range (i.e., 12-40 dB) and for a log-normal distribution centered at 26 dB, due to the very low channel frequency selectivity.

Fig. 7 plots $\overline{D}$ versus time, for different mobility scenarios, i.e., for different values of $\sigma$. Although, the value of $\overline{D}$ tends to stabilize in an interval of few ms, it is interesting to notice that a channel with high $\Gamma$ variance, due to shadowing, leads to better performance in terms of expected delay. This counter-intuitive result is due to the combination of shadowing effects and ACL strategy performance.

Fig. 8 plots $\overline{D}$ versus time, for different service flow bandwidth requirements, i.e., for different values of $\lambda$ when $L_{\text{max}} = 0.001$. The increase of $\lambda$ leads to an increase of $\overline{D}$, making it difficult to ensure requested QoS. For values of $\lambda > 1.5$ PDU per time frame, QoS requirements cannot be guaranteed anymore on the $\Gamma$ range. In such case, $\Gamma$ range on which QoS should be guaranteed, service flow bandwidth (e.g., to allow more than one PDU transmission per time frame) or service flow QoS (e.g., PDU loss rate and expected delay) should be renegotiated with the BS.

V. CONCLUSIONS

An adaptive cross-layer (ACL) strategy that jointly optimizes PHY and MAC parameters of an OFDM based network to meet users’ QoS was presented. ACL strategy is based on a queuing theory model. The theoretical results were shown to perfectly match the simulation results. ACL strategy was tested on different scenarios of user mobility. Simulation results show that the ACL strategy is able to promptly adapt to channel quality variations and to meet QoS requirements using the minimum amount of bandwidth. Further studies are required on this topic to account for delayed or inaccurate CQI, impact of other QoS requirements (e.g., jitter, maximum delay) and different service flow characteristics (more accurate traffic models), practical implementation constraints (e.g., limited buffer size), and more sophisticated ARQ protocols.

REFERENCES