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E-CLEMA: A cross-layer design for improved quality of service in mobile WiMAX networks

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Summary

In this paper, an efficient cross-layer design that performs joint adaptation of the physical (PHY) and application layers of a mobile WiMAX network is proposed. The design takes into account channel state and performance information from the PHY and medium access control (MAC) layers, respectively. It uses a decision algorithm to evaluate this information, specify unfavorable conditions regarding low channel quality and increased congestion, and take measures by coordinating modulation order, transmission power, and media encoding rate, toward improved overall quality of service (QoS) offered to the user. Extensive simulation results show that the proposed design achieves considerably reduced packet loss and power consumption, combined with increased throughput as compared to a typical mobile WiMAX system. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: adaptive modulation; cross-layer design; IEEE 802.16e; multi-rate applications; OFDMA; power control

1. Introduction

Modern wireless communication systems are characterized by the need for advanced quality of service (QoS) provision to their end-users combined with efficient utilization of the scarce available bandwidth. This is achieved by using powerful and computationally simple adaptation procedures, such as adaptive modulation and error control, adaptive media encoding rate, and power control, aiming on improving the overall system performance. A challenging issue is the satisfaction of the varying and sometimes contradictory performance requirements posed by different classes of applications, especially under hostile transmission conditions caused by the users' mobility, poor channel quality, and limited resource availability.

Traditionally, communication systems adopt a layered approach in their attempt to provide efficient QoS to their end users. Although this approach aims to the efficient operation of each individual layer of the protocol stack, it can result in the overall system performance degradation. The main reason for this is the independent, and sometimes conflicting, operation of the separate adaptation mechanisms residing in

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each layer. Typically, this is resolved with the introduction of a cross-layer design that coordinates and combines these mechanisms toward improved overall system performance [1].

A very promising technology in the field of wireless broadband communication systems is WiMAX that complies with the IEEE 802.16 family of standards [2,3]. In order to enhance the system performance and support user mobility, the IEEE 802.16e amendment has adopted the Orthogonal Frequency Division Multiple Access (OFDMA) scheme. This scheme provides multiplexing in both uplink and downlink directions by subdividing the available bandwidth into multiple orthogonal frequency subcarriers. The user data streams are also divided into several parallel substreams each of which is modulated and transmitted on a separate orthogonal subcarrier. Thus, using efficient subcarrier bit and power allocation algorithms, the OFDMA scheme manages to offer multi-user diversity and increased robustness against frequency-selective fading and inter-symbol interference (ISI). Systems complying with the IEEE 802.16e amendment are usually referred to as *mobile WiMAX systems*.

In the recent bibliography [4–11], many proposals on cross-layer designs over OFDMA communication systems can be found. In Reference [4], the problem of joint congestion control at the transport layer and OFDMA scheduling at the medium access control (MAC) layer for hybrid wireline–wireless networks is formulated as a network utility maximization problem. A cross-layer design for the joint packet scheduling and radio resource allocation in an OFDMA system is considered in Reference [5]. In Reference [6], the problem of joint channel allocation, modulation level, and power control in a multi-cell network is addressed by considering a synergy between the physical and access layers and introducing two classes of heuristic algorithms. A cross-layer design between the MAC and Physical (PHY) layers for packet scheduling and resource allocation is considered in Reference [7] with the aim to maximize the overall utilization while satisfying each user rate requirements. In Reference [8], the issue of adaptive coding and modulation and resource and power allocation in an IEEE 802.16e system taking into consideration resource and power constraints is addressed. Its aim is to reduce the total transmitted power in order to achieve interference reduction and system capacity increase. By exploiting the acknowledgement feedback received by the mobile nodes, [9] proposes a cross-layer design for downlink time division multiplexing (TDM)—OFDMA systems assuming imperfect channel state information and unknown interference in slow fading channels. In Reference [10], the problem of efficient broadcast/multicast video delivery over IEEE 802.16e networks is tackled. Its aim is to address the issues of synchronization, energy efficiency, and video quality, achieve increased coverage and spectrum efficiency, and finally guarantee improved video quality.

A heuristic cross-layer mechanism for real-time traffic over the OFDM-based IEEE 802.16 networks that interacts with the PHY, MAC, and application layers is introduced in Reference [11]. The main idea behind this mechanism, which will be therein referred to as "*CLEMA*" (*Cross-Layer Encoding and Modulation Adaptation*), is the coordination of the adaptive modulation capability of the PHY layer and the adaptive media encoding rate of modern real-time encoders at the application layer, leading to reduced packet losses and system capacity improvement as experienced at the MAC layer. However, despite its improved performance, CLEMA does not utilize all the adaptation capabilities provided by WiMAX in order to achieve channel quality improvement. One of them is power control. It is well known that the efficient adaptation of the transmission power can lead to better overall system performance by improving the channel quality in cases of congestion and achieving reduced power consumption in case of favorable channel conditions, especially in mobile environments such as mobile WiMAX. Motivated by the above, the purpose of this paper is to extend the design proposed in Reference [11] by including the transmission power adaptations into the overall cross-layer design, and improve the performance of mobile WiMAX, in terms of packet loss, throughput, and power consumption. Moreover, the simulation environment used for the performance evaluation is enhanced to be applied to mobile WiMAX systems employing the OFDMA scheme. This environment includes an enhanced traffic scheduler that performs resource allocation to the connections taking into account both their QoS requirements as well as their perceived channel quality. Additionally, the simulation environment employs a more realistic channel model that provides path loss as well as short-term fading and leads to more accurate performance evaluation results. The proposed design will be hereafter referred to as "*E-CLEMA*" (*Extended-CLEMA*).

The rest of this paper is organized as follows. Section 2 provides an overview of the proposed E-CLEMA design. Section 3 describes in detail the

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decision algorithm that is the core of this design. In Section 4, the performance of E-CLEMA is evaluated through a set of simulations. Finally, Section 5 contains conclusions and plans for future work.

2. System Model

The proposed cross-layer design for IEEE 802.16e networks is split into two parts, namely the base station (BS) part and the mobile station (MS) part, residing at the BS and the MSs, respectively [11]. An outline of the proposed design operation for both uplink and downlink directions is shown in Figure 1. For comparison purposes, the messages regarding power control not included in Reference [11] are underlined.

The BS part collects information regarding each connection's performance status, i.e., packet timeout rate, mean delay, channel state conditions, and transmission power on both directions (uplink and downlink). Based on this information, a decision algorithm residing inside the BS part determines the encoding mode, modulation order, and transmission power level

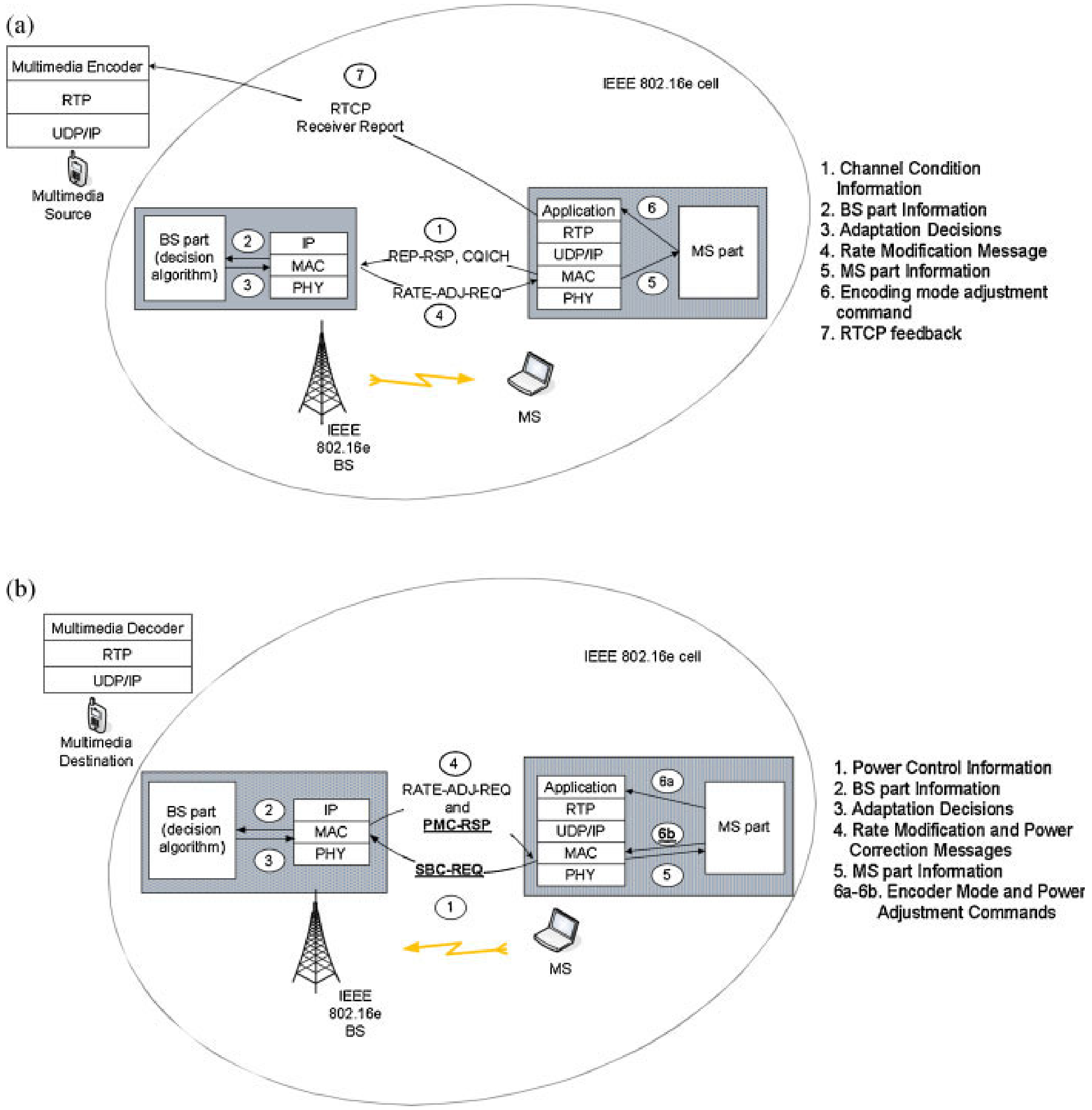

Fig. 1. E-CLEMA system model: (a) downlink, (b) uplink.

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of each MS. Channel conditions for the uplink are known from the BS PHY layer, while for the downlink they can be obtained through IEEE 802.16(e) signaling [2,3] (see arrow (1) in Figure 1a). Packet timeout rate and mean delay for all active connections in both directions can be provided by the BS MAC layer (see arrow (2) in Figure 1a and b). Transmission power levels for the downlink can be obtained by the BS PHY layer, while for the uplink they can be derived by signaling messages defined in the IEEE 802.16(e) standards [2,3] (see arrow (1) in Figure 1b) that will be described below.

The BS part decisions regarding encoding mode adjustments are transferred to the MS part through the BS MAC layer (see arrow (3) in Figure 1a and b) using a specially defined MAC management message referred to as *Rate Adjustment Request* (*RATE-ADJ-REQ*) described below (see arrow (4) in Figure 1a and b). The MS MAC layer transfers the received rate modification request to the MS part that is responsible for the communication with the application layer (see arrow (5) in Figure 1a and b). The MS part decides on the connections that should be affected and sends proper cross-layer messages to the application layer (see arrow (6) in Figure 1a and arrow (6a) in Figure 1b). On the uplink direction, the application layer can perform the proper adjustments, e.g., by tuning the data encoder to produce the required overall media-encoding rate. In the downlink direction, the MS has to notify the distant traffic sources for the necessary encoding adjustments, using an Application layer Real-Time Control Protocol (RTCP) feedback message, to suggest a new encoding mode to the senders (see arrow (7) in Figure 1a).

The BS MAC layer is also responsible for transferring the power control messages containing the BS part instructions regarding the transmission power levels on the uplink. These instructions are transferred to the MS MAC layer (see arrow (4) in Figure 1b) through an IEEE 802.16e power control message, e.g., the *Power Control Mode Change Response* (*PMC_RSP*) [3]. The MS MAC layer will in turn inform the MS part accordingly (see arrow (5) in Figure 1b). Again, the MS part is responsible for distributing the available transmission power to its connections (see arrow (6b) in Figure 1b).

It should be noted that all management messages exchanged between the network entities for the operation of the E-CLEMA design are either signals available in the IEEE 802.16(e) and RTCP standards or can be easily derived from such standardized signals. In the following, although all message exchanges necessary for the completion of the presentation are being reviewed, emphasis is given to power control related message signals not considered in Reference [11].

2.1. Channel Quality Information

In order to increase the robustness of downlink transmissions, the BS requires information regarding the quality of the signal received by the MSs. For this, each MS sends channel quality measurements to the BS using standard IEEE 802.16(e) signaling either periodically, through the *Channel Quality Information Channel* (*CQICH*), or on demand, through the *Channel Measurement Report Request and Response* (*REP-REQ, REP-RSP*) messages [2,3] (see arrow (1) in Figure 1a).

2.2. Rate Modification Message

The BS part decisions regarding recommended media encoding rate adjustments are transferred to the MS part using the *Rate Adjustment Request* (*RATE-ADJ-REQ*) message defined in Reference [11] (see arrow (4) in Figure 1a and b). This message contains the BS part recommendation in the form of a target overall mean media encoding rate either for the downlink or the uplink and its syntax is shown in Table I.

Message type 67 is determined as "reserved" in both References [2] and [3], meaning that it is left unused for future purposes. The "Direction" parameter declares uplink or downlink direction. The "Total Rate Recommended" parameter contains the recommendation of the BS part in kb/s. Considering that this refers to the total transmission rate for an MS, the size of 32 bits allows rates up to approximately 4.3 Gb/s per direction.

2.3. Encoding Mode Adjustments

For the downlink direction, the MS application has to inform the traffic source for media encoding rate adjustments. This can be performed through a standard *Application Layer RTCP Receiver Report* (*RR*) message. Application layer messages are part of the

Table I. RATE-ADJ-REQ message.

Syntax	Size
RATE-ADJ-REQ_Message_Format( ) {	
Management Message Type = 67	8 bits
Direction	1 bit
Total Rate Recommended	32 bits
}	

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extensions of Real-time Transport Protocol (RTP) for RTCP-based feedback, as defined in Reference [12], and can be used to transport application-defined data directly from the receiver to the sender application. Such a message can be sent either immediately or at the next regular time instance, depending upon the RTCP mode and the bandwidth available for RTCP messages [12].

2.4. Power Control Information Exchange

Each MS has to provide the BS with the necessary information regarding its maximum available as well as its current transmission power. This exchange of information is achieved through messages such as the *Subscriber Station Basic Capability Request* (*SBC-REQ*) message and the *Channel Measurement Report Response* (*REP-RSP*) message (see arrow (1) in Figure 1b). Based on the results of the decision algorithm, the BS has to notify the MSs of the required transmission power modifications (see arrow (4) in Figure 1b). The standard [2,3] provides various power correction messages such as the *Power Control Mode Change Response* (*PMC_RSP*), *Ranging Response* (*RNG-RSP*), and *Fast Power Control* (*FPC*) messages.

3. Decision Algorithm

In this section, the operation of the decision algorithm executed in the BS part of the proposed E-CLEMA system is described. This algorithm takes into account the connections' packet loss rates and mean delay and performs adaptation of the modulation order, transmission power and media-encoding rate. Its aim is to improve QoS provision to the connections in terms of packet loss rate, throughput, and power consumption.

Let us present first the details of the system model and QoS parameters of interest.

Considering transmissions between one BS and K MS connections, using N OFDMA subcarriers, with each OFDMA frame consisting of L time slots and containing packets from $\widehat{K}$ connections ($\widehat{K} \leq K$), the most important system model parameters are the following:

(a) $\gamma_{k,n}$ is the Carrier to Interference plus Noise Ratio (CINR) of the k^{th} connection, $k \in \{1, 2, \ldots, K\}$, on the n^{th} subcarrier, $n \in \{1, 2, \ldots, N\}$. CINR is estimated by the BS based on the measurements it performs on the received signals (uplink) as well as on the channel state information it receives on a periodic basis from the MSs (downlink).

(b) b_k denotes the number of bits per OFDMA symbol of the k^{th} connection. $b_k \in \{0, 1, \ldots, M\}$ where M is the maximum number of bits per transmitted OFDMA symbol. b_k^{e} denotes the expected number of bits per OFDMA symbol as a result of a modulation order adaptation.

(c) $I_{k,n}$ is a variable indicating whether the subcarrier n is allocated to connection k. Thus,

$$I_{k,n} = \begin{cases} 1, & \text{if subcarrier } n \text{ is allocated to connection } k \\ 0, & \text{elsewhere} \end{cases}$$

(d) $\text{BER}_{k,n}$ denotes the bit error rate (BER) experienced by the k^{th} connection on the n^{th} subcarrier. It is a function of $\gamma_{k,n}$ and b_k: $\text{BER}_{k,n} = f(\gamma_{k,n}, b_k)$. BER_k denotes the mean BER experienced by connection k on its allocated set of subcarriers: $\text{BER}_k = (\sum_{n=1}^{N} \text{BER}_{k,n} \cdot I_{k,n})/(\sum_{n=1}^{N} I_{k,n})$; Similarly, $\text{BER}_{k,n}^{\text{e}}$ and BER_k^{e} denote the expected values of $\text{BER}_{k,n}$ and BER_k, respectively, as a result of a modulation order adaptation: $\text{BER}_{k,n}^{\text{e}} = f(\gamma_{k,n}, b_k^{\text{e}})$, $\text{BER}_k^{\text{e}} = (\sum_{n=1}^{N} \text{BER}_{k,n}^{\text{e}})/N$.

(e) $P_{k,n}$ is the transmission power of the k^{th} connection on the n^{th} subcarrier and P_k is the total transmission power of the k^{th} connection on its allocated set of subcarriers. Thus, $P_k = \sum_{n=1}^{N} P_{k,n} \cdot I_{k,n}$.

(f) ΔP denotes the interval between two consecutive power levels.

The QoS parameters used by the proposed decision algorithm are the following:

(i) $R_{\text{err}}(k)$ is the packet error rate of the k^{th} connection, i.e., the percentage of packets that are lost due to channel errors.

(ii) $R_{\text{timeout}}(k)$ is the packet timeout rate of the k^{th} connection, i.e., the percentage of packets that are lost due to expiration.

(iii) $R_{\text{loss}}(k) = R_{\text{err}}(k) + R_{\text{timeout}}(k)$ is the total packet loss rate experienced by the k^{th} connection.

(iv) d_{k} is the mean delay experienced by the k^{th} connection while α_k, ε_k and d_{max_k} are the BER tolerance, maximum tolerable loss rate, and maximum acceptable delay of the k^{th} connection, respectively.

(v) μ_k is the encoding mode of the k^{th} connection. $\mu_k \in \{0, 1, 2, \ldots, D\}$, depending on the corre-

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sponding multi-rate application, where D is the highest encoding mode.

(vi) $\delta_k = \frac{R_{\text{err}}(k)}{R_{\text{loss}}(k)}$, is the percentage of packet errors with respect to the total loss rate of the k^{th} connection. δ_k is the main QoS parameter used in the decision algorithm as it represents the packet errors contribution to the overall connection packet loss rate and allows the determination of the nature of the packet losses experienced by a connection.

(vii) δ_{low}, δ_{med} and δ_{high} are the thresholds upon which the algorithm decides on the appropriate adaptation actions. If $\delta_k > \delta_{\text{high}}$, the connection is considered to be suffering almost exclusively by packet errors that are the result of significantly unfavorable channel conditions. Otherwise, if $\delta_{\text{med}} < \delta_k < \delta_{\text{high}}$ the connection is still considered to be suffering mainly by hostile transmission conditions, but a considerable part of its total packet losses is the result of packet timeouts. If $\delta_{\text{low}} < \delta_k < \delta_{\text{med}}$, most of the connection packet losses are the result of packet timeouts but a significant percentage of them is the result of packet errors caused by poor channel quality. Finally, if $\delta_k < \delta_{\text{low}}$ the connection is considered to be suffering almost exclusively by unacceptable delays that lead to packet timeouts.

(viii) β_k is a threshold indicating whether the delay of the k^{th} connection is close to its maximum acceptable bound $d_{\max_k}$ (i.e., if $\frac{d_k}{d_{\max_k}} > \beta_k$).

We use the packet loss as the basic criterion for the operation of the E-CLEMA as it directly affects the QoS observed by each connection. The maximum tolerable packet loss rate ε_k as well as the maximum acceptable delay $d_{\max_k}$ can be different for each connection based on its individual QoS characteristics and requirements. However, the usual case considered in this paper is that connections belonging to a specific traffic class have the same packet loss rate and delay thresholds. Additionally, the discrimination between packet error and packet timeout rates through the introduction of the δ parameter allows the decision algorithm to determine the nature of packet losses and thus, take the most appropriate adaptation decisions.

An outline of the decision algorithm, the flow chart of which is illustrated in Figure 2, executed at the BS part for each MS connection will be presented next.

The algorithm is initiated in regular time instances and takes adaptation decisions every time the

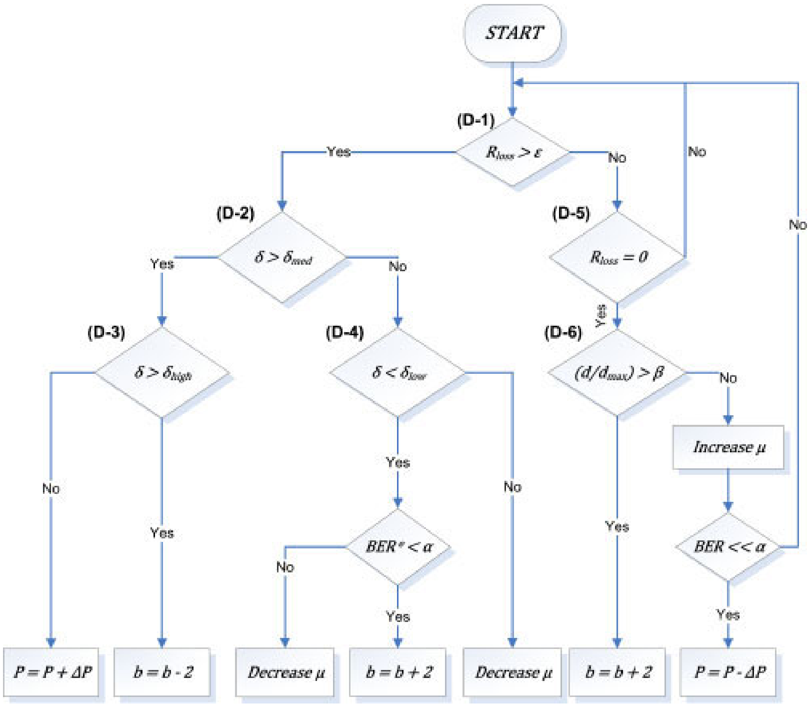

Fig. 2. Decision algorithm flow chart per connection.

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k^{th} connection faces unacceptable packet loss rates that lead to a degradation of the provided QoS (see (D-1) in Figure 2)[‡]. The actions to be taken depend on the nature of these losses, as follows.

(1) *In case* $\delta_k > \delta_{\text{med}}$ (see (D-2) in Figure 2), *most of the losses are due to packet errors caused by bad channel conditions*. The decision depends on the packet errors contribution to the overall packet losses experienced by the specific connection:
  i. *If* $\delta_k > \delta_{\text{high}}$ (see (D-3) in Figure 2), *i.e., the connection loss rate is almost exclusively caused by packet errors*, the algorithm concludes that the transmission conditions are significantly unfavorable resulting in high BER. In this case, the most appropriate action is to decrease the modulation order thus allowing the connection to achieve higher channel error resilience and increase robustness against interference. The BS part selects then the highest modulation order that will restore the loss rate to acceptable values, according to a BER versus CINR curve, such as the one included in Reference [13], and instructs the MAC layer accordingly. The MAC layer sends the required primitives to the PHY for the modulation order change and informs the MS through the Downlink Access Definition (DL-MAP), for downlink changes and UL-MAP, for uplink changes, fields of the next MAC time frame.
  ii. *Otherwise* ($\delta_{\text{med}} < \delta_k < \delta_{\text{high}}$), *a significant percentage of packet losses are caused by packet timeouts*. The algorithm assumes that the connection is under congestion conditions. In this case, a decrease of the modulation order that results in significant reduction of the transmission rate would most probably cause an immediate increase of the connection packet timeouts. Therefore, the BS part will instruct for a transmission power increase that will improve the connection CINR without reducing the transmission rate.

(2) *In case* $\delta_k < \delta_{\text{med}}$ (see (D-2) in Figure 2), *most of the losses are the result of unacceptable delays that cause packet timeouts*. The action to be performed depends on the contribution of these timeouts to the overall packet losses:
  i. *If* $\delta_k < \delta_{\text{low}}$ (see (D-4) in Figure 2), *the overall loss rate is caused almost exclusively by packet timeouts*. The algorithm can safely conclude that the transmission rate is very low and unable to satisfy the connection transmission speed requirements. In this case, *if the expected BER is lower than the BER tolerance* (see D-5 in Figure 2), the BS part instructs for an increase of the modulation order which will increase the transmission rate and thus will reduce the losses caused by timeouts. In different case, the BS part instructs for a media encoding rate decrease. As previously, the error rate induced by the candidate modulation order can be predicted using a BER versus CINR curve.
  ii. *In other case* ($\delta_{\text{low}} < \delta_k < \delta_{\text{med}}$), *a significant percentage of packet losses are caused by errors due to the poor channel conditions* that do not allow a modulation order increase. The BS part instructs the MS part for a media encoding rate reduction in order to moderate timeouts.

To achieve an efficient performance under all possible conditions, the algorithm must make adaptation decisions also when the conditions for a specific connection are improved. Thus, when the loss rate decreases significantly (see (D-6) in Figure 2), the algorithm may decide to switch to a higher modulation order that will increase the transmission rate, reduce the connection power in order to achieve power efficiency, or increase the media encoding rate and improve the QoS. The specific action depends on the mean delay, as follows:

1) *If* $\frac{d_k}{d_{\max_k}} > \beta_k$ (see (D-7) in Figure 2), *the mean delay is close to the connection delay bound*. The algorithm instructs for a modulation order upgrade that will immediately increase the transmission rate and reduce the mean delay.
2) *Otherwise, if the mean delay is relatively low compared to the delay bound* ($\frac{d_k}{d_{\max_k}} < \beta_k$) (see (D-7) in Figure 2), the algorithm instructs for a media encoding rate increase to improve the QoS provided to the user. However, this increase should be performed carefully as it may lead to increased traffic and possible delay bound violations. In any case, the percentage of this increase should be relevant to the difference between the current value of the mean delay and the delay bound. Additionally, if the channel conditions for the specific connection are such that significantly

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[‡] D-1, D-2, ..., D-8 refer to the Decision Points shown in Figure 2.

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low BER occurs (see (D-8) in Figure 2), the algorithm may also instruct for a reduction of the transmitting and/or receiving power in order to reduce power consumption, improve power efficiency and reduce possible interference to neighboring nodes.

The previously described decision algorithm can be implemented as follows:

```
for $k = 1$ to $K$ do
    if $R_{\text{loss}}(k) > \varepsilon_k$ then
        if $\delta_k > \delta_{\text{medium}}$ then
            if $\left(\delta_k > \delta_{\text{high}}\right)$ then
                $b_k \leftarrow b_k - 2$
            else
                $P_k = P_k + \Delta P$
            end
        else if $(\delta_k < \delta_{\text{low}})$ then
            $b_k^{\text{e}} \leftarrow b_k + 2$
            for $n = 1$ to $N$ do
                $\text{BER}_{k,n}^{\text{e}} \leftarrow f\left(\gamma_{k,n}, b_k^{\text{e}}\right)$
            end
            $\text{BER}_k^{\text{e}} \leftarrow \frac{1}{N} \cdot \sum_{n=1}^{N} \text{BER}_{k,n}^{\text{e}}$
            if $\text{BER}_k^{\text{e}} < \alpha_k$ then
                $b_k \leftarrow b_k^{\text{e}}$
            else
                Decrease $\mu_k$
            end
        else
            Decrease $\mu_k$
        end
    else if $R_{\text{loss}}(k) \cong 0$ then
        if $\left(\frac{d_k}{d_{\max_k}} > \beta_k\right)$ then
            $b_k^{\text{e}} \leftarrow b_k + 2$
            for $n = 1$ to $N$ do
                $\text{BER}_{k,n}^{\text{e}} \leftarrow f\left(\gamma_{k,n}, b_k^{\text{e}}\right)$
            end
            $\text{BER}_k^{\text{e}} \leftarrow \frac{1}{N} \cdot \sum_{n=1}^{N} \text{BER}_{k,n}^{\text{e}}$
            if $\text{BER}_k^{\text{e}} < \alpha_k$ then
                $b_k \leftarrow b_k^{\text{e}}$
            end
        else
            increase $\mu_k$
            if $\text{BER}_k \ll \alpha_k$ then
                $P_k = P_k - \Delta P$
            end
        end
    end
end
```

The complexity of the above algorithm is $O(K \cdot N)$. A typical system has to perform adaptive modulation for each of the K connections based on the CINR value of each of the N subcarriers, leading to a complexity similar to the proposed algorithm.

It should be noted that the performance of the proposed E-CLEMA design is strongly affected by the specific values of the thresholds δ_{low}, δ_{med}, δ_{high} and β_k, that activate modulation order, transmission power, and media encoding rate adaptations. Clearly, all the thresholds jointly determine the algorithm's ''sensitivity'' regarding adaptation decisions. For example, the value of δ_{low} determines the point that activates a modulation order increase and thus it has an immediate effect on the transmission rate. A small value of δ_{low}, that does not allow for frequent increases, results in low transmission rate that may lead to unacceptable packet timeouts. In contrast, a large value of δ_{low}, that increases the modulation order more frequently, may lead to unacceptable packet errors. Clearly, the values of these thresholds directly affect the overall performance and they should be adjusted dynamically, based on several parameters such as the available bandwidth or the channel quality. The dynamic determination of these values is out of the scope of this paper and is left for future work.

4. Performance Evaluation Results and Discussion

The previously discussed E-CLEMA design has been evaluated by means of computer simulation and various performance evaluation results have been obtained. Performance was compared with the CLEMA mechanism introduced in Reference [11] and a typical IEEE 802.16e system that performs adaptive modulation at the PHY layer and media encoding adjustments at the application layer separately and independent of each other. The overall simulation model was constructed in C++ and its individual subsystems, illustrated in Figure 3, will be described next.

4.1. Traffic Generator

It generates one video variable-length traffic frame every 40 ms for each connection, starting at a random instance within the first 40 ms of a simulation run. The maximum encoding rate for each connection depends on the feedback received from the cross-layer mechanism.

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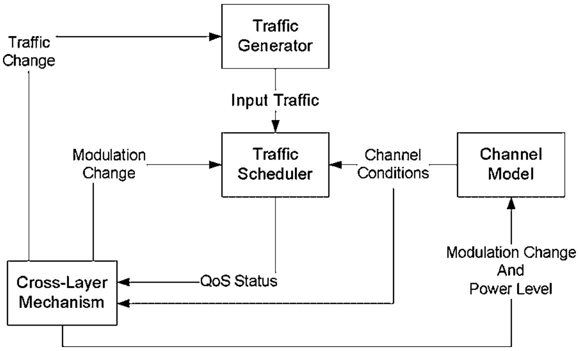

Fig. 3. Simulation model outline.

4.2. Traffic Scheduler

It performs the resource allocation to the connections as shown in Figure 3. It receives input traffic from the traffic generator, information regarding the connection modulation order changes by the cross-layer mechanism and channel conditions information from the channel model. In our simulation we use the "Frame Registry Tree Scheduler" (FRTS) described in Reference [14], a deadline-based scheduler for IEEE 802.16 networks that uses a tree structure in order to provide differentiated service to connections based on their QoS requirements. Its aim is to perform resource allocation that guarantees QoS agreements between the BS and the MSs, perform packet discrimination for the fair dropping of excess traffic during congestion and eliminate processing during time frame creation. Additionally, an OFDMA allocator was used [15] to allocate to each MS sufficient resources for satisfying its QoS requirements while taking into account the wireless channel quality. Both schedulers support all the traffic classes defined by the IEEE 802.16(e) standards, namely Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS), Extended Real-Time Polling Service (e-rtPS), Non-Real-Time Polling Service (nrtPS), and Best Effort (BE) and can guarantee the provision of improved service based on each class' characteristics and prioritization. In the current simulation model, rtPS video traffic was used as E-CLEMA aims at the performance improvement of multi-rate real-time applications.

4.3. Channel Model

A novel part of the simulation model used for the performance evaluation of E-CLEMA is the channel model that simulates the system channel conditions by providing path loss and short-term fading. Bit errors are randomly produced for each connection, according to its modulation scheme information provided by the cross-layer mechanism, with a mean rate according to the BER versus CINR curve included in Reference [13]. Path loss is assumed to be $P_r(dBm) = P_0 + L - 10n\log(d)$ where P_r is the received power, P_0 is the transmitted power, L is the link budget [16], d is the distance between BS and MS, and n is the path loss exponent that, assuming a dense urban environment, equals to 4 [17]. Short-term channel fading envelopes are considered to be Rayleigh distributed assuming the well-known Jakes spectra model with a maximum Doppler frequency shift of 128.2 Hz. Carrier frequency is set to 2.3 GHz and the number of subcarriers N is set to 64. The MSs are randomly distributed in the area of an IEEE 802.16e cell of 1 km radius and move within the cell range with a velocity of 60 km/h.

4.4. Cross-Layer Mechanism

It executes the proposed design's decision algorithm described in the previous section and decides on each connection modulation order, transmission power level and media encoding rate based on the QoS information received by the traffic scheduler and channel condition information received by the channel model. The cross-layer mechanism decisions are transferred to the traffic scheduler, the channel model and the traffic generator that perform the appropriate adjustments.

For the system employing the CLEMA mechanism introduced in Reference [11], the cross-layer mechanism does not perform power control and decides only on the modulation order and media-encoding rate of each connection.

For a standard IEEE 802.16e system, which will be referred to as "legacy system," the operations performed by the cross-layer mechanism are split into two parts that operate independently. On the one hand, the *physical layer adapter* is the entity that instructs the traffic scheduler for modulation order adjustments based solely on the channel conditions information provided by the channel model. On the other hand, the *application layer adapter* instructs the traffic generator for traffic changes based on the connections total packet loss rates. The BS receives channel conditions information by each MS periodically. The traffic generator receives RTCP feedback by each MS every 5 s according to Reference [18].

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4.5. Simulation Scenario

The simulation scenario considers an increasing number of MSs, each one with one downlink video connection. The systems' performance is measured in terms of throughput, packet loss rate, mean delay, and total transmitted power. To focus on the improvement process, the BS is considered as the traffic source for all connections and assumed minimum delay for the transmission of signaling messages at the radio interface. The modulation schemes used are QPSK, 16-QAM, and 64-QAM and the code rate equals 1/2. The system maximum transmission power was set to 20 W. The time frame length is set to 1 ms and the maximum transmission rate is 120 Mb/s (for 64-QAM). In order to achieve lower processing complexity in the simulation model, 7% of this data rate is reserved for the above connections, while the rest is assumed dedicated to other kinds of traffic. This percentage is lower than the one used in Reference [11] to cope with the increased complexity of the OFDMA allocator. Extensive simulation experiments have shown, by trial and error, that the following values for the thresholds and delay parameters result in the best performance with respect to packet loss rate, throughput, and power consumption: $\delta_{\text{low}} = 0.05$, $\delta_{\text{med}} = 0.5$, $\delta_{\text{high}} = 0.99$ and $\beta_k = 0.95$. The CLEMA and E-CLEMA decision algorithms are initiated every 40 ms, as this is the period used by the traffic generator for the creation of traffic frames. The same period is used for the modulation order adaptations employed by the legacy system. A longer period would make the decision algorithms less responsive to changes, while a shorter one is not expected to provide improved performance considering the period used for the traffic generation. For consistency and to obtain fair comparisons in all simulations, the initial states and channel conditions are the same for all systems under consideration (Table II).

Table II. Simulation parameters.

Parameter	Value
Traffic frame creation period	40 ms
Mean traffic rate per MS	63 kb/s
Path loss model	$P_r(dBm) = P_0 + L - 10n\log(d)$
Path loss exponent (n)	4
Maximum Doppler frequency shift	128.2 Hz
Carrier frequency	2.3 GHz
Number of subcarriers (N)	64
Cell radius	1 km
MS velocity	60 km/h
Modulation schemes	QPSK, 16-QAM, 64-QAM
Code rate	1/2
System maximum transmission power	20 W
Time frame length	1 ms
Maximum Transmission Rate	8.4 Mb/s
δ_{low}	0.05
δ_{med}	0.5
δ_{high}	0.99
β_k	0.95

4.6. Simulation Results

Figure 4 illustrates the total packet loss rates as a function of the number of MSs of the legacy system, the system employing the CLEMA mechanism [11] and the new system employing the proposed E-CLEMA design. Packet losses are the sum of packet errors and packet timeouts. All systems managed to efficiently adapt to the wireless channel quality fluctuations by instructing proper modulation order adjustments and maintained the packet error rate in values around 10^{-3}. Thus, the dominant part of the packet loss rate is the packet timeouts. As can be seen from Figure 4, the legacy system shows unacceptable packet losses in cases of congestion, while the proposed E-CLEMA design achieves considerably improved packet loss rates as the number of MSs increases. This happens because in the legacy system adaptive modulation is performed based solely on the channel state information received by the MSs and is totally unaware of the loss rates experienced by the MSs. Additionally, RTCP feedback messages are exchanged between the MSs and the real-time sources every 5 s, and thus are unable to quickly detect unacceptable packet losses and enable the MSs to efficiently react by reducing the media encoding rate on time. On the other hand, the coordinated adaptation of modulation, media encoding rate, and transmission power of each connection employed by the E-CLEMA design, provides the system with the ability to accommodate to frequent channel quality fluctuations and heavy traffic situations.

Figure 4 also depicts the performance improvement of the described E-CLEMA design against the CLEMA mechanism [11]. This performance improvement is due to the power control functionality introduced in the proposed E-CLEMA design. The adaptation of the transmission power prevents frequent modulation order decreases that significantly reduce the transmission rate in heavy congestion situations. Thus, in cases of unfavorable channel conditions it reduces packet error rates by increasing the transmission power and avoids packet timeout rates as it does not affect the connections' transmission rate.

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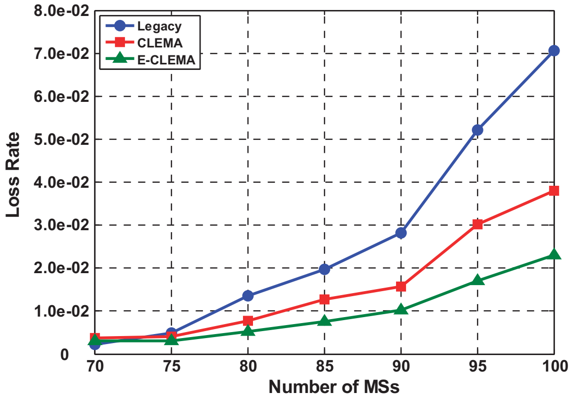

Fig. 4. Packet loss rate versus the number of MSs.

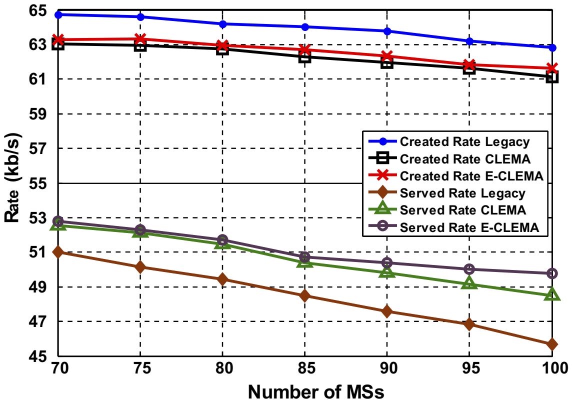

Fig. 5. Created and served rates.

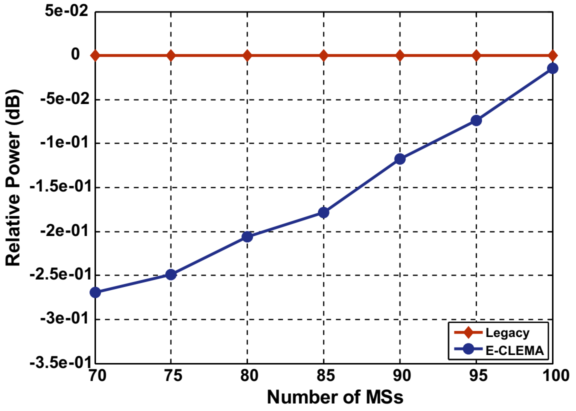

Fig. 6. Relative power per subcarrier.

Figure 5 depicts the created and served MAC layer rates per MS for the three systems under consideration. All the systems have created rates that follow a declining course due to the fact that the operation of the RTCP protocol becomes more intensive as the number of MSs increases. The legacy system has a slightly increased created rate, in a scale of 1 kb/s, compared to CLEMA and E-CLEMA. However, the legacy system does not have the ability to efficiently handle these encoding rates while the system employing E-CLEMA manages to maintain higher served rates, in an average scale of 3 kb/s. Note once again that the proposed E-CLEMA design has slightly improved served rates as compared to the CLEMA mechanism. Mean delay is only slightly, in the scale of μs, reduced by the use of the E-CLEMA, since this is mainly affected by the deadline-based scheduler (FRTS) [14] operation, that schedules traffic as close to its deadline as possible in any case.

Figure 6 depicts the relative transmission power per subcarrier in the system employing the proposed E-CLEMA design. Although the use of power adaptations is more intensive, as the number of the MSs increases and congestion becomes more intense, the mean power consumption per subcarrier is lower than in the case of the legacy system. This happens because the power decrease performed when the channel quality is favorable, is more intense than the power increase during heavy congestion situations.

5. Conclusions

In this paper, a cross-layer design for the performance improvement of multi-rate real-time applications over IEEE 802.16e networks was presented. By taking into account information from the PHY and MAC layers, a decision algorithm performs joint adaptive modulation and power control at the PHY layer and encoding rate adjustment at the application layer. Simulation results showed that the system employing this design manages to accommodate an increased number of connections by efficiently coordinating the operations of adaptive modulation, power control, and encoding rate and guaranteeing reduced packet loss rates and increased throughput. Our future plans include the extension of the described cross-layer design operation to support horizontal and vertical handovers toward other wireless communication systems and an analytical model for the derivation of the decision algorithm thresholds and the theoretical evaluation of the proposed design's performance.

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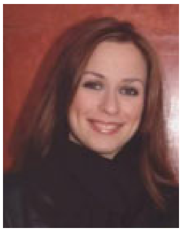
Authors' Biographies



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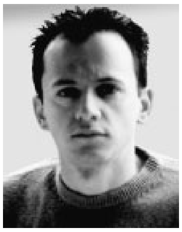

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