Mobility Management in Heterogeneous Mobile Communication Networks through an Always Best Connected Integrated Architecture

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Abstract. The operation of a cross-layer mechanism for the performance improvement of real-time applications over IEEE 802.16(e) networks is presented. This mechanism utilizes wireless channel quality and quality of service information, coordinates the operation of the adaptation mechanisms of the Physical and Application layers and uses the handover as one of the ways to improve the system performance. With the use of the information received from the Physical and Medium Access Control layers, the cross-layer mechanism coordinates appropriately the adaptations of the modulation order and the transmitted power at the Physical layer as well as the media encoding rate at the Application layer and instructs for handover initiations. The aim of this mechanism is to avoid situations of inefficient operation, caused by the independent operation of the adaptation mechanisms residing in different layers of the protocol stack. The performance of the proposed cross-layer mechanism is evaluated through simulation as well as theoretical analysis that allows for the dynamic adaptation of its operational parameters.

Keywords: cross-layer design, burst profile, encoding rate, power control, handover initiation, continuous flow model.

1 Dissertation Summary

1.1 Introduction

Recently, the field of wireless communication networks has been greatly developed in research as well as commercial level. These networks are characterized by the need for Quality of Service (QoS) provision to the end users, combined with the efficient utilization of the available bandwidth. The dynamic nature of the wireless medium combined with the great variety of the, often contradictory, requirements posed by the various traffic categories, are two factors that seriously affect the performance of

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modern wireless communication systems, especially in terms of multimedia applications.

Thus, each layer of the protocol stack is enhanced with a variety of adaptation mechanisms to allow the adaptation of its operation to the rapidly varying system conditions, aiming at the maximization of its performance. However, the completely independent operation of these mechanisms and the inability of information exchange between non-adjacent layers, as posed in typical networks that follow the discrete layers model, may result in significant degradation of the provided Quality of Service to the end users and the overall system performance.

In order to address this issue, a "violation" of the traditional discrete layers' architecture with the adoption of mechanisms that employ the principles of Cross-Layer Design is proposed. These mechanisms coordinate the operation of individual adaptation mechanisms and provide flexible and effective solutions in many areas. For example, such mechanisms can improve the performance of protocols initially designed for wired networks, the performance of real-time applications even under severe conditions or the efficiency of mobility management procedures. Although a number of proposals in this area can be found in the relevant bibliography, the interest in the design of novel cross-layer solutions keeps constantly increasing as new standards, protocols and technologies are being developed.

Another issue that greatly affects the performance of modern communication systems is the end users' mobility. Users on the move, in an area where various access technologies overlap, demand the intermittent operation of their applications with minimum data loss caused by the inevitable handovers. Thus, the development of efficient mobility management mechanisms that ensure the intermittent service of the end users is necessary.

Motivated by the above, this dissertation proposes a cross-layer mechanism for the QoS provision enhancement in real-time applications over IEEE 802.16(e) networks [1]. This mechanism utilizes channel quality and end user QoS information, coordinates the operation of the Physical (PHY) and Application layer adaptation mechanisms and uses the handover as a way to improve the QoS provision.

The main contribution of this dissertation is the integration of the adaptive modulation, power control, multi-rate encoding and handover initiation in a cross-layer mechanism. The role of this mechanism is the coordination of these functionalities in order to achieve overall system performance and end user QoS improvement. Additionally, the modeling and theoretical analysis of the operation of the cross-layer mechanism allows for the dynamic adaptation and optimization of its operational parameters, thus resulting in the maximization of its performance.

1.2 Related Work

In the recent bibliography a great variety of proposals on cross-layer schemes designed for numerous kinds of wireless networks and applications can be found. In this section, a brief overview of such proposals, based on their main field of operation, is provided.

A large number of recent proposals on cross-layer designs aim at improving the QoS provision and the overall performance of the system they are applied to. Such proposals include rate control algorithms based on the experienced channel conditions, that aim to normalize the unpleasant variations of the wireless medium quality. Other mechanisms introduce efficient schemes to avoid unnecessary retransmissions and improve the system throughput. Adaptive coding schemes that take into account both the QoS requirements of the applications and the conditions of the wireless medium are also suggested.

For example, the authors in [2] present a general cross-layer feedback architecture for mobile wireless environments. This design uses a “tuning layer” for every layer of the wireless protocol stack. Each tuning layer provides an interface to the data structures that determine the operation of its corresponding protocol layer. The tuning layers are used by “protocol optimizers” that contain the cross-layer optimization algorithms and comprise the “optimization subsystem” that operates concurrently with the wireless protocol stack. The overall scheme’s purpose is the improvement of the Transmission Control Protocol (TCP) feedback mechanism’s throughput.

Radio Resource Management (RRM) is an issue of great importance in wireless communication networks. The air interface and hardware resources need to be efficiently utilized to achieve increased throughput and channel capacity and avoid unpleasant phenomena such as interference. Several proposals on cross-layer cooperative designs regarding RRM can be found in the recent bibliography. The majority of them introduce efficient schemes for power control, resource allocation, admission control and packet scheduling.

[3] proposes a joint Medium Access Control (MAC)-Physical layer resource management algorithm that performs packet scheduling, subcarrier allocation and power control for wireless Orthogonal Frequency Division Multiplexing (OFDM) networks. The above operations are performed taking into account the impact of channel state information on the performance of packet scheduling and power allocation. Its aim is the maximization of the system power efficiency and overall performance, guaranteeing in parallel QoS provision and fairness.

Recent literature on cross-layer solutions for mobility issues mainly focuses on the support of the handover procedure. Many proposals in this area aim at the reduction of the handover execution time and the mitigation of unfavorable phenomena, e.g., increased packet loss rate, call dropping, etc., induced by a handover.

For example, a cross-layer mechanism that considers mobility at different layers of the protocol stack in order to achieve better quality for Voice over IP (VoIP), videoconferencing, and other real-time applications is proposed in [4]. This mechanism introduces an entity called “Mobility Manager” that monitors connection parameters, performs handover decisions and provides the applications with information regarding handover events and network parameters. Each application takes proper adaptation decisions based on the received information.

As seen from the above, most cross-layer designs in the area of mobility management are employed with the aim either to facilitate the handover procedure and avoid possible problems, or to adapt the parameters of different layers of the wireless protocol stack to the varying channel conditions. On the contrary, in this dissertation the cross-layer design is extended to consider the handover as one of the possible ways to improve the system performance together with the existing QoS enhancement mechanisms, i.e., adaptive modulation, adaptive encoding and power control. Thus, in cases of unfavorable system conditions, the proposed cross-layer mechanism may attempt to improve the performance by instructing either an adaptation of the modulation order, the transmission power or the encoding mode, or the initiation of a handover.

Additionally, in the area of cross-layer power control and resource management, most proposals in the recent bibliography use cross-layer schemes with the aim to reduce the overall power consumption that is the result of the end users' computational activities and to minimize the interference by utilizing information from the other layers of the protocol stack. On the contrary, the cross-layer mechanism proposed in this dissertation uses the power control as a way to combat unfavorable conditions in the wireless medium. This aim is achieved with proper adaptations of the connections' transmission power level in order to avoid unnecessary adaptations of the modulation order that greatly affect the data rate and consequently the packet losses caused by congestion.

1.3 The Proposed Cross-Layer Mechanism

The proposed cross-layer mechanism was developed in three versions. The first version is called "Cross-Layer Encoding and Modulation Adaptation" (CLEMA) mechanism. This mechanism utilizes information provided by the Physical and MAC layers and, using a decision algorithm it derives new operational parameters for the Physical and Application layers, which can improve the performance of real-time applications. The main idea is to coordinate the adaptive modulation capability of the Physical layer and the multi-rate data-encoding capability of modern real-time applications in order to avoid inefficiencies caused by their independent operation. Simulations show that the proposed mechanism can assist 802.16 systems better adapt to frequent channel and traffic changes, leading to considerably reduced packet loss rates, especially under heavy traffic conditions.

Despite its improved performance, CLEMA does not utilize all the adaptation capabilities provided by IEEE 802.16 networks 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 IEEE 802.16e. Motivated by the above, the CLEMA mechanism is extended by including the transmission power adaptations into the overall cross-layer design, and improve the system performance, in terms of packet loss, throughput and power consumption. This designed is referred to as "E-CLEMA" (Extended-CLEMA). 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 system.

The main motivation of the third version of the proposed cross-layer mechanism is that in future communication systems, applications will be dynamically adaptable to the varying system conditions, regarding channel quality and congestion, up to a certain limit specified by the users. After that point, in order to improve performance, the only alternative, besides rejecting some users, is to handover to another cell or access network. The third version of the proposed mechanism, referred to as M-

CLEMA (Mobile CLEMA), incorporates the handover initiation into the E-CLEMA decision algorithm by considering two different modes: reactive and proactive. The reactive mode combats unacceptable packet losses first by instructing adaptations of the PHY and Application layers, and only when no further adaptation is possible, it instructs for handover execution. In contrast, the proactive one prefers to first examine the possibility of a handover execution rather than instructing for adaptations of the connections' burst profile, encoding mode or transmission power.

2 Results and Discussion

The cross-layer mechanism proposed in this dissertation is based on the architectural framework introduced in [5], which consists of N layers and a cross-layer optimizer.
According to that, the optimization process is performed in three steps, namely *Layer Abstraction, Optimization* and *Layer Reconfiguration*.
The rate at which the above steps are repeated depends on the variance of the channel conditions and the applications' requirements.

2.1 CLEMA: Cross-Layer Encoding and Modulation Adaptation

The system under consideration consists of a IEEE 802.16 cell managed by a Base Station (BS) and a number of Subscriber Stations (SSs). The CLEMA mechanism, described in detail in references [6-8], is split into two parts, namely the BS part and the SS part, residing at the BS and each SS, respectively. The operation of the proposed mechanism (Fig. 1) for both uplink and downlink directions can be divided in three main phases.

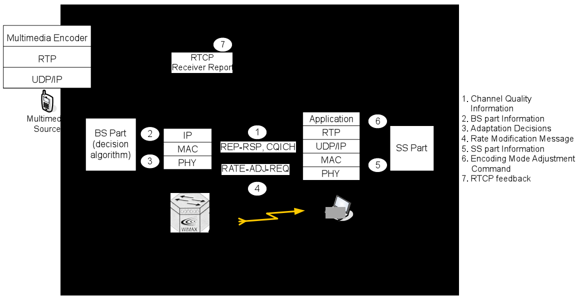

Fig. 1: The CLEMA mechanism on the downlink direction

In *Phase 1*, the BS part starts by collecting all the required information regarding the performance status of each of its active connections. This information includes channel state conditions on the uplink and downlink directions, packet timeout rate and mean delay and is provided to the BS part through standard IEEE 802.16e signaling.

In *Phase 2*, the BS part uses the collected information to run a decision algorithm (Fig. 2) and select between modifying the encoding mode, or using a different burst profile. This decision is taken separately for each SS aiming at providing an improved QoS.

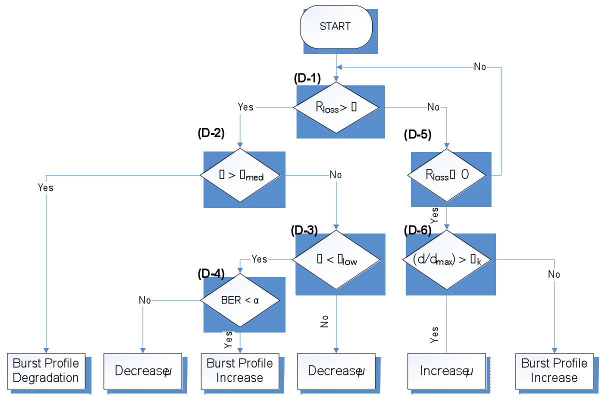

Fig. 2: CLEMA decision algorithm flow chart

In *Phase 3*, the various system components are informed of the BS part decisions through standard IEEE 802.16e signaling and perform the required adjustments. For encoding mode adjustments the BS MAC layer transfers to the SS MAC layer its decisions. These decisions are transferred using the *Rate Adjustment Request (RATE-ADJ-REQ)* message defined in [6]:

Table 1: 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
}	

The performance of the CLEMA mechanism was compared against atypical IEEE 802.16 system that performs the operations of Adaptive Modulation at the Physical layer and multi-rate encoding at the Application layer separately and independent to each other.

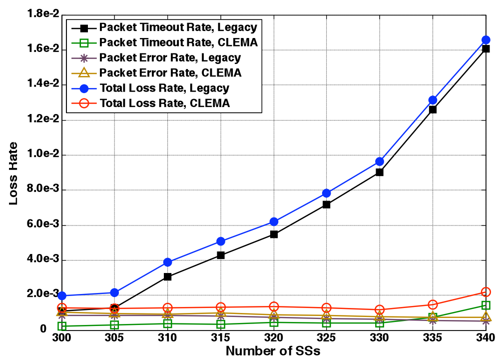

Fig. 3: Packet Loss rate vs. the number of SSs

As seen in Fig. 3, the system employing the CLEMA mechanism clearly outperforms the legacy system in terms of packet loss rate, as the independent operation of the two mechanisms in the typical system results in inefficient operation.

2.2 E-CLEMA: Extended CLEMA

The E-CLEMA mechanism described in [9-11], extends the CLEMA mechanism by including the transmission power adaptations into the overall cross-layer design.

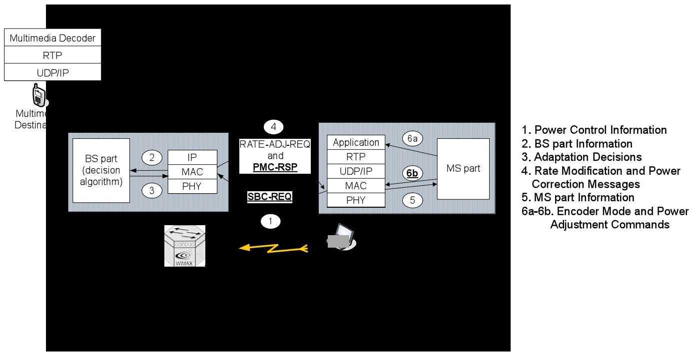

Fig. 4: The E-CLEMA mechanism on the uplink direction

The system under consideration consists of a IEEE 802.16e cell, managed by a Base Station (BS) and a number of Mobile Stations (MSs) moving within the area of coverage. The E-CLEMA mechanism is split into two parts, namely the BS part and the MS part, residing at each BS and MS, respectively. The operation of the proposed mechanism (Fig. 4) can be divided in three main phases.

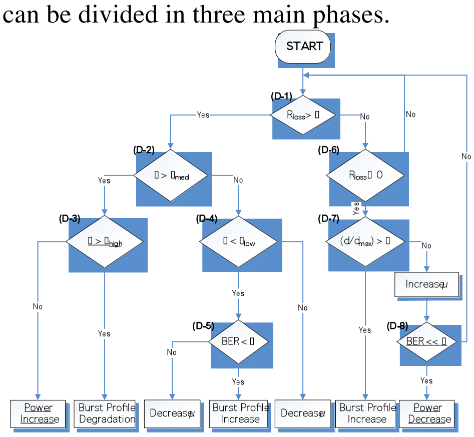

Fig. 5: E-CLEMA Decision Algorithm Flow Chart

In *Phase 1*, the BS part starts by collecting all the required information regarding the channel state conditions and transmission power on both directions, and packet timeout rate and mean delay and is provided to the BS as in the case of the CLEMA mechanism through standard IEEE 802.16e signaling.

In *Phase 2*, the BS part uses the collected information to run a decision algorithm (Fig. 5) and select between a) modifying the encoding mode, b) using a different burst profile, or c) altering the transmission power level. This decision is taken separately for each MS aiming at providing an improved QoS.

In *Phase 3*, the various system components are informed of the BS part decisions and perform the required adjustments.

The performance of the E-CLEMA mechanism was compared against the CLEMA mechanism and a legacy system that performs the operations of Adaptive Modulation and multi-rate encoding separately and independent to each other.

As seen in Fig. 6, the introduction of the transmission power adaptations into the overall cross-layer design of the E-CLEMA mechanism results in significantly improved performance in terms of packet loss rate.

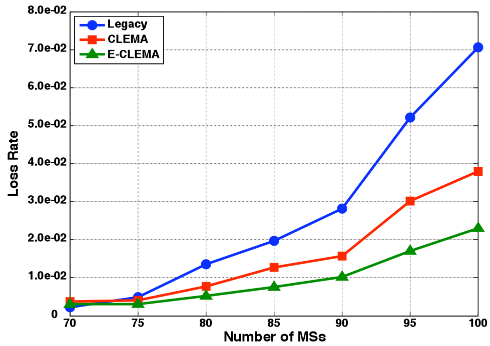

Fig. 6: Packet Loss Rate vs. the number of MSs

2.3 M-CLEMA: Mobile CLEMA

The third version of the proposed mechanism is called “M-CLEMA” (Mobile-CLEMA) [12-13] and incorporates the handover initiation into the E-CLEMA decision algorithm by considering two different modes: reactive and proactive. The reactive mode combats unacceptable packet losses first by instructing adaptations of the PHY and Application layers, and only when no further adaptation is possible, it instructs for handover execution. In contrast, the proactive one prefers to first examine the possibility of a handover execution rather than instructing for adaptations of the connections’ burst profile, encoding mode or transmission power.

The operation of the M-CLEMA mechanism (Fig. 7) can be divided in three main phases.

In *Phase 1*, the BS part collects information regarding the channel state conditions and transmission power on both directions, and packet timeout rate and mean delay and is provided to the BS as in the case of the E-CLEMA mechanism.

In *Phase 2*, the BS part uses the collected information to run a decision algorithm (Fig. 8) and select between a) modifying the encoding mode, b) using a different burst profile, c) altering the transmission power level, or d) suggesting a handover execution. This decision is taken separately for each MS aiming at providing an improved QoS.

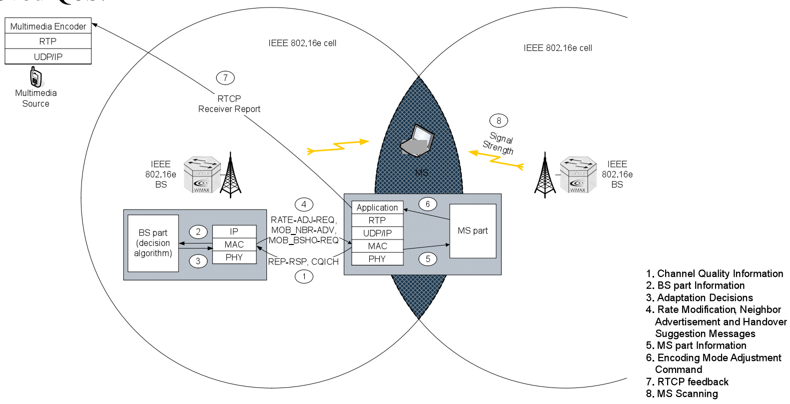

Fig. 7: M-CLEMA mechanism on the downlink direction

In *Phase 3*, the various system components are informed of the BS part decisions and perform the required adjustments.

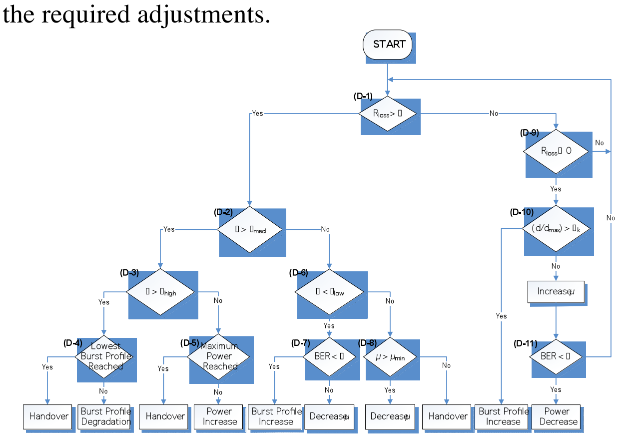

Fig. 8: Reactive M-CLEMA decision algorithm flow chart

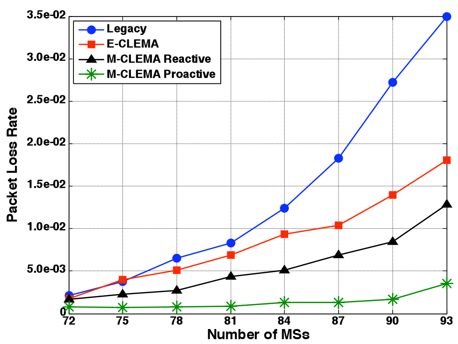

Fig. 9: Packet Loss Rate vs. the number of MSs

The performance of the M-CLEMA mechanism (proactive and reactive) was compared against the legacy system and a system that employs the E-CLEMA mechanism. As seen in Fig. 9, the systems employing the two modes of the M-CLEMA mechanism outperform the E-CLEMA and Legacy systems in terms of packet loss rate as they allow a MS to achieve improved performance by a neighboring cell, and thus improve its performance, by performing a handover before losing its connectivity with the current BS.

2.4 Theoretical Analysis

The operation of the system employing the CLEMA mechanism is modeled with the use of a Continuous Flow Model (CFM) [14]. This model consists of a "fluid" queue with inflow and outflow processes being characterized by flow rates, while its content is defined by the volume of the stored fluid.

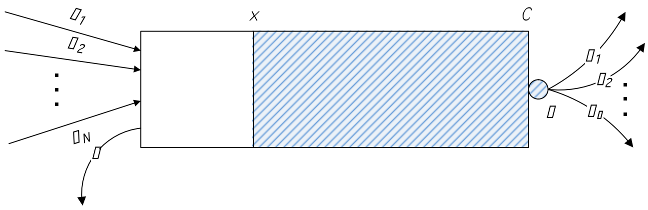

Fig. 10: Multiple source Continuous Flow Model

The queue size is finite. Thus, in case the queue is full, the excessive flow can't be served and it overflows. The basic storage unit of this model is an OFDMA symbol, therein referred to as "symbol". Each connection is considered as a continuous data flow with maximum tolerated latency (waiting time in the queue) equal to $S_{\max}$.

The basic parameters of this model are the following:

i. $\alpha(t)$: Inflow rate in symbols/s.

ii. $\varphi(t) = c/T_f$: Constant service rate in symbols/s (the MAC layer time frame has duration of T_f s and serves c symbols).

iii. $C = c \cdot S_{\max}/T_f$: Queue size in symbols, so that an overflow occurs when the mean waiting time of a symbols exceeds the value of $S_{\max}$.

iv. $x(t)$: Buffer load in symbols.

v. $\eta(t)$: Outflow rate in symbols/s.

vi. $\lambda(t)$: Overflow rate in symbols/s.

Let a source that generates data with encoding rate $\mu_d(t)$bits/s, $d \in \{1,2,...,D\}$ and modulation order $b_m(t)$bits/symbol, $m \in \{1,2,...M\}$. The maximum tolerable loss rate is ε, while the mean delay is $\overline{S}$. A system consisting of a fluid queue and a single data source is modeled as a $D \times M \times (C+1)$ state Markov chain with each state being represented by the parameters: (encoding mode, modulation order, buffer load). The main QoS parameter taken into account by the decision algorithm is defined as

$\delta = R_{error} / R_{loss}$ where R_{error} is the data source error rate and R_{loss} is the data source total loss rate and δ_{low} and δ_{med} are its two thresholds defining the adaptations of the modulation order and the encoding mode. The transition matrix of the Markov Chain is derived by the decision algorithm of the CLEMA mechanism. From the invariant distribution of the Markov Chain minimum closed set, performance evaluation results, such as error rate, overflow rate and mean delay can be derived.

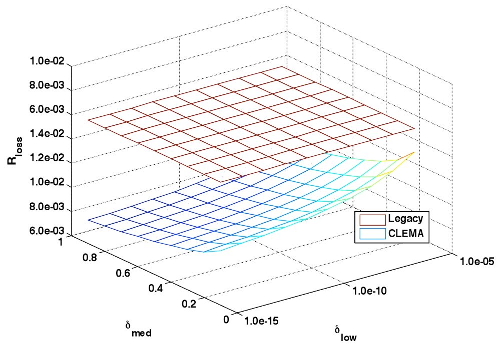

Fig. 11: R_{loss} vs. the values of δ_{low} and δ_{med}

Fig. 11 depicts the total loss rate of the data source as a function of the thresholds δ_{low} and δ_{med}. As it can be seen, the best performance is achieved as the value of δ_{med} increases and the value of δ_{low} decreases.

3 Conclusions

In this dissertation, a cross-layer mechanism for the performance improvement of real-time applications over IEEE 802.16e metropolitan area networks has been proposed. The mechanism, utilizes information from the PHY, MAC and Application layers and decides on the connections' modulation order, transmission power and encoding mode, or suggests for handover execution. According to extensive simulation results, the proposed mechanism achieves significantly improved performance in terms of packet loss rate, power consumption, throughput and system capacity. The modeling and theoretical analysis of the proposed mechanism allows for the dynamic adaptation of its operational parameters, thus increasing its flexibility and its responsiveness to the wireless channel variations and, finally, enhancing its ability to maximize the system performance.

References

1. IEEE Std 802.16e, "IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems. Amendment 2:

Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1", Feb. 2006.

2. J. Villalon, P. Cuenca, L. Orozco-Barbosa, Y. Seok and T. Turletti, "Cross-Layer Architecture for Adaptive Video Multicast Streaming Over Multirate Wireless LANs", *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 4, pp. 699-711, May 2007.
3. Y. J. Zhang and K. B. Letaief, "Cross-Layer Adaptive Resource Management for Wireless Packet Networks With OFDM Signaling", *IEEE Transactions on Wireless Communications*, vol. 5, no. 11, pp. 3244-3254, Nov. 2006.
4. M. Bernaschi, F. Cacace, G. Lannello and M. Vellucci, "Mobility Management for VoIP on Heterogeneous Networks: Evaluation of Adaptive Schemes", *IEEE Transactions on Mobile Computing*, vol. 6, no. 9, pp. 1035-1047, Sept. 2007.
5. S. Khan, Y. Peng, and E. Steinbach, "Application-Driven Cross-Layer Optimization for Video Streaming over Wireless Networks", *IEEE Communications Magazine*, vol. 44, no. 1, pp. 122-130, Jan. 2006.
6. D. Triantafyllopoulou, N. Passas, A. Salkintzis, and A. Kaloxylos, "A Heuristic Cross-Layer Mechanism for Real-Time Traffic over IEEE 802.16 Networks", *Wiley's International Journal of Network Management*, special issue on "Management Solutions for QoS Support over the Entire Audio-Visual Service Distribution Chain", vol. 17, no. 5, pp. 347-361, Sept./Oct. 2007.
7. D.-K. Triantafyllopoulou, N. Passas, and A. Kaloxylos, "A Cross-Layer Optimization Mechanism for Multimedia Traffic over IEEE 802.16 Networks", Proc. *13th European Wireless 2007*, April 2007.
8. D. Triantafyllopoulou, N. Passas, A. Salkintzis and A. Kaloxylos, "A Heuristic Cross-Layer Mechanism for Real-Time Traffic in IEEE 802.16 Networks", Proc. *18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2007 (PIMRC '07)*, pp. 1-5, Sept. 2007.
9. D. Triantafyllopoulou, N. Passas, L. Merakos, N. Sagias and P. T. Mathiopoulos, "E-CLEMA: A Cross Layer Design for Improved Quality of Service in Mobile WiMAX Networks", *Wiley's Wireless Communications and Mobile Computing*, accepted for publication (available online).
10. D. Triantafyllopoulou, N. Passas and A. Kaloxylos, "Cross-Layer Adaptation for Real-Time Broadband Multimedia over IEEE 802.16e Networks", Proc. *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting 2008 (BMSB '08)*, pp. 1-6, April 2008.
11. D. Triantafyllopoulou, N. Passas, G. Lampropoulos and A. Kaloxylos, "Joint Application and Physical Layer Adaptation for Improved Performance in Wireless Networks", Proc. *3rd IEEE International Symposium on Wireless and Pervasive Computing 2008 (ISWPC '08)*, pp. 256-260, May 2008.
12. D. Triantafyllopoulou, N. Passas, A. Kaloxylos and L. Merakos, "Coordinated Handover Initiation and Cross-Layer Adaptation for Mobile Multimedia Systems", *IEEE Transactions on Multimedia*, special issue on "Quality-Driven Cross-Layer Design for Multimedia Communications", accepted for publication (to appear Aug. 2009).
13. D. Triantafyllopoulou, N. Passas and A. Kaloxylos, "Integration of Handover in a Cross-Layer Mechanism for Mobile Multimedia Systems", Proc. *IEEE International Conference on Communications 2009 (ICC '09)*, June 2009.
14. Y. Wardi and B. Melamed, "Variational Bounds and Sensitivity Analysis of Traffic Processes in Continuous Flow Models", *Springer's Discrete Event Dynamic Systems*, vol. 11, no. 3, pp. 249-282, July 2001.