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***Abstract*—The theoretical analysis of a cross-layer mechanism for improving the quality of service of real-time applications in wireless networks is presented. The mechanism coordinates adaptations of the modulation order at the Physical layer and the media encoding mode at the Application layer, to improve packet loss rate, throughput and mean delay. With the use of Continuous Flow Modeling, the system is considered as a "fluid" queue with inflow and outflow rates representing its traffic generation and service rates, respectively. Each data source is modeled as a Markov chain, from the steady-state of which the optimal adaptation thresholds of the cross-layer mechanism are derived. Performance evaluation results show that the optimized operation of the mechanism attains a significant performance improvement compared to both the sub-optimal mechanism, and a legacy system.**

I. Introduction

Recently, cross-layer designs for the performance improvement of wireless communication systems have attracted an increasing research interest. Most proposals in this area coordinate the operation of various adaptation mechanisms residing in different layers of the wireless protocol stack to attain efficient resource utilization and better Quality of Service (QoS) provision. This requires proper adaptation decisions based on information regarding the overall system conditions. In the recent bibliography, many cross-layer design proposals deal with the appropriate adaptation of various operational parameters based on the values of dynamic [1] or static [2], [3] thresholds.

In this paper, we focus on a cross-layer mechanism, introduced in [3], for the performance improvement of real-time applications in mobile WiMAX networks [4]. Although this mechanism was introduced for mobile WiMAX, it can be applied to any wireless network that provides similar adaptation and signaling capabilities. The said mechanism, referred to as *Cross-Layer Encoding and Modulation Adaptation (CLEMA)*, coordinates the adaptive modulation capability at the Physical layer and the multi-encoding mode feature at the Application layer to avoid inefficiencies caused by their independent operation. However, in [3], the values of the thresholds used by the CLEMA decision algorithm for activating modulation order and encoding mode adaptations are statically determined after extensive simulation experiments. To overcome this inefficiency and derive optimal threshold values, this paper proposes a Continuous Flow Model (CFM) [5], [6] consisting of a "fluid" queue whose inflow and outflow processes represent the traffic generation and service processes, respectively. The optimal values of the thresholds that activate adaptations of the modulation order or the encoding mode are the ones that lead to optimal system performance in terms of packet loss rate and mean delay. Performance evaluation results show that using optimal values, significant improvement can be attained compared to both a legacy system that adapts the modulation order and encoding mode separately and independently of each other, and CLEMA using static, sub-optimal values.

The rest of this paper is organized as follows. Section II provides an overview of the CLEMA mechanism operation. Section III describes the theoretical analysis of the proposed system using CFM. In Section IV, the system model is described in detail, leading to the derivation of optimal threshold values. Section V presents comparative results that reveal the performance improvement attained with optimal CLEMA. Finally, Section VI contains conclusions and plans for future work.

II. CLEMA: Cross-Layer Encoding and Modulation Adaptation

The system under consideration is a cellular wireless network, where each cell consists of a Base Station (BS) and a number of Mobile Stations (MSs) within the BS area of coverage. CLEMA is split into two parts, namely the BS part and the MS part, residing at the BS and each MS, respectively. The operation of CLEMA (Figure 1) for both the uplink and the downlink directions can be divided in three main phases.

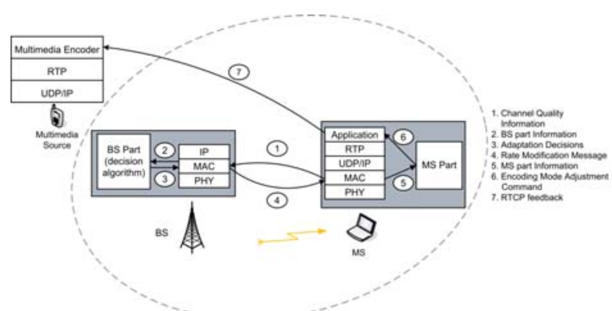

Fig. 1. The CLEMA mechanism for the downlink

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 in the uplink and downlink directions, packet timeout rate and mean delay. In Phase 2, the BS part uses the collected information to run a decision algorithm (described below) and decide between modifying the encoding mode or using a different burst profile, which is defined as the modulation and coding scheme used. In Phase 3, the various system components are informed of the BS part decisions and perform the required adjustments.

Assuming N active connections in a cell, the QoS parameters used by the CLEMA decision algorithm are the following:

i. $R_{err,i}$ is the packet error rate of the i^{th} connection, $i \in \{1, 2, \ldots, N\}$, i.e., the percentage of packets lost due to channel errors.

ii. $R_{timeout,i}$ is the packet timeout rate of the i^{th} connection, i.e., the percentage of packets that were lost due to deadline expiration (packet delay has exceeded maximum acceptable delay).

iii. $R_{loss,i} = R_{timeout,i} + R_{err,i} \cdot (1 - R_{timeout,i})$ is the total packet loss rate of the i^{th} connection.

iv. S_i is the mean delay of the i^{th} connection.

v. μ_i is the encoding mode of the i^{th} connection. $\mu_i \in \{1, 2, \ldots, D\}$, depending on the corresponding multi-rate application.

vi. ε_{max_i} and S_{max_i} are the maximum tolerable loss rate and maximum acceptable delay of the i^{th} connection, respectively, while ε_{min_i} is a parameter indicating very low loss rate (low loss rate indicator).

vii. $\delta_i = \frac{R_{err,i}}{R_{loss,i}}$ is the fraction of lost packets (whose loss was due to channel errors) for the i^{th} connection. δ_i gives information on the nature of the packet losses experienced by a connection, which is valuable for the adaptation decision process.

viii. δ_{low}, δ_{med} and β are the thresholds upon which the algorithm decides on the appropriate adaptation actions.

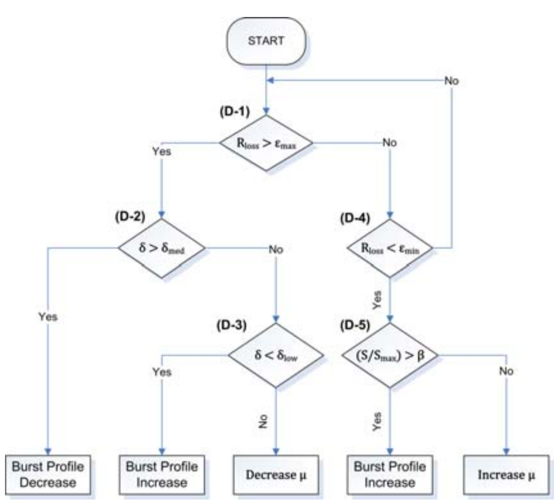

Fig. 2. CLEMA decision algorithm flow chart

The algorithm is initiated at regular time instants and takes proper adaptation decisions based on the packet loss rate of each connection i (see (D-1) in Figure 2). The actions to be taken depend on the nature of these losses, as follows:

1) In case $\delta_i > \delta_{med}$ (D-2), most of the losses are due to packet errors caused by unfavorable channel conditions, so the most appropriate action is to switch to a more robust burst profile.
2) In case $\delta_i < \delta_{med}$, most of the losses are the result of delays that cause packet timeouts. The action to be performed depends on the contribution of these timeouts to the overall packet losses:
   i. If $\delta_i < \delta_{low}$ (D-3), the overall loss rate is caused almost exclusively by packet timeouts and the BS part instructs for an increase of the burst profile.
   ii. If $\delta_{low} < \delta_i < \delta_{med}$, a significant percentage of packet losses is caused by errors due to poor channel conditions, and the BS part instructs the MS part for a media encoding rate reduction.

To achieve an efficient performance under all possible conditions, the algorithm must make adaptation decisions also when the QoS for a specific connection is improved. Thus, when the loss rate decreases significantly, $R_{loss,i} < \varepsilon_{min_i}$ (D-4),

1) If $\frac{S_i}{S_{max_i}} > \beta_i$ (D-5), the mean delay is close to the connection delay bound. The algorithm instructs for a burst profile upgrade, which will immediately increase the data rate, and reduce the mean delay.
2) Otherwise, if the mean delay is relatively low compared to the delay bound ($\frac{S_i}{S_{max_i}} < \beta_i$), the algorithm instructs for a media encoding rate increase to improve the QoS provided to the user.

III. Analysis using a Continuous Flow Model

A. General Continuous Flow Model

The operation of the system that employs the CLEMA mechanism can be modeled as a CFM [5], [6], such as the one depicted in Figure 3. This model consists of a "fluid" queue whose inflow and outflow processes are characterized by flow rates, while its content is defined by the volume of the stored fluid. The size of the queue is finite. Thus, in case the queue is full, the excess flow cannot be absorbed, leading to overflow. The basic storage unit of this model is an Orthogonal Frequency Division Multiple Access (OFDMA) symbol. In the rest of this paper, for presentation purposes, an OFDMA symbol will be referred to as "symbol". Each connection is fed by a data source producing a continuous data flow with maximum tolerable delay S_{max}.

The basic parameters of the CFM are the following:

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

ii. $\varphi(t)$: Constant service rate in symbols/s (the MAC layer time frame is considered to have a duration of T_f seconds and serve c symbols).

iii. $C = c \cdot \frac{S_{max}}{T_f}$: Queue size in symbols. Its value is such that overflow occurs when the delay of a queued symbol exceeds the maximum tolerable value S_{max}.

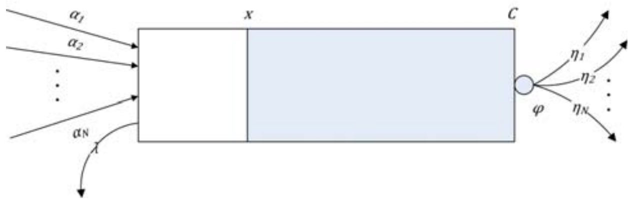

Fig. 3. Multiple source CFM

iv. $x(t)$: Queue load in symbols.
v. $\eta(t)$: Outflow rate in symbols/s.
vi. $\lambda(t)$: Overflow rate in symbols/s.

Let N identical data sources, each with a variable encoding rate equal to $\mu_{i,d}(t)$ bits/s, $d \in \{1, 2, ..., D\}$ and modulation order $b_{i,m}(t)$ bits/symbol, $m \in \{1, 2, ..., M\}$, $i \in \{1, 2, ..., N\}$, where D and M are the number of discrete encoding modes and modulation orders, respectively. The inflow rate of each source is $\alpha_i(t) = \frac{\mu_{i,d}(t)}{b_{i,m}(t)}$ while the total inflow rate is $\alpha(t) = \sum_{i=1}^{N} \alpha_i(t)$. The buffer load $x(t)$ is described by the differential equation

$$\frac{dx(t)}{dt^+} = \begin{cases} 0, & \text{if } x(t) = 0 \text{ and } \alpha(t) \le \varphi(t) \\ 0, & \text{if } x(t) = C \text{ and } \alpha(t) - \varphi(t) \ge 0 \\ \alpha(t) - \varphi(t), & \text{else} \end{cases} \quad (1)$$

The outflow rate is defined as

$$\eta(t) = \begin{cases} \varphi(t), & \text{if } x(t) > 0 \\ \alpha(t), & \text{if } x(t) = 0 \end{cases}.$$

The total overflow rate $\lambda(t)$ is

$$\lambda(t) = \begin{cases} \alpha(t) - \varphi(t), & \text{if } x(t) = C \text{ and } \alpha(t) - \varphi(t) \ge 0 \\ 0, & \text{else} \end{cases},$$

while the overflow rate $\lambda_i(t)$ of each source is proportional to the percentage of the source inflow rate with respect to the total system inflow rate. The total overflow volume during the time interval $[0,\ T]$ is $L = \int_0^T \lambda(\tau)\, d\tau$. Thus, the total overflow rate during the time interval $[0,\ T]$ is $R_{overflow} = \frac{L}{\int_0^T \alpha(\tau) d\tau}$. This corresponds to the connection packet timeout rate $R_{timeout}$ defined in Section II.

B. Transmission over the wireless channel

The data that are successfully served by the queue are transmitted over the wireless medium. The data loss rate owing to errors over the wireless channel of the i^{th} source, assuming independent and uniformly distributed bit errors, is $\zeta_i(t) = \eta_i(t) \cdot \left(1 - (1 - BER_i(t))^{b_{i,m}(t)}\right)$ where $\eta_i(t)$ is the outflow rate, and $BER_i(t)$ is the Bit Error Rate (BER) of the i^{th} source. $BER_i(t)$ is a function of the Signal to Noise Ratio (SNR) $\gamma_i(t)$ and the modulation order $b_{i,m}(t)$: $BER_i(t) = f(\gamma_i(t), b_{i,m}(t))$.

The total error rate in symbols/s is defined as $\zeta(t) = \sum_{i=1}^{N} \zeta_i(t)$. The total loss due to wireless channel errors during $[0,\ T]$ is $E = \int_0^T \zeta(\tau)\, d\tau$. The total error rate is $R_{err} = \frac{E}{\int_0^T \eta(\tau) d\tau}$. Finally, the total loss rate of the described system is $R_{loss} = R_{overflow} + R_{err} \cdot (1 - R_{overflow})$. The decision algorithm, executed at the BS part of CLEMA, has to determine the appropriate values of $\mu_{i,d}(t)$ and $b_{i,m}(t)$ in order to minimize R_{loss}.

C. Calculation of loss and mean delay

In this section, the main QoS parameters based on which the CLEMA decision algorithm adjusts the data source modulation order and encoding mode are calculated using the previously described CFM.

Let us first consider a system that consists of a single data source, the fluid queue and the wireless medium. The source generates data with an 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 data source mean delay is denoted as $\bar{S}$. It is assumed that during the observation interval $[0,\ T]$ the functions $\alpha(t)$ and $\varphi(t)$ are piecewise constant with a finite number of "jumps". In this case, the function $x(t)$ is piecewise linear, while the functions $\eta(t)$ and $\lambda(t)$ are piecewise constant as well. The decision algorithm has to determine the appropriate values of $\mu_d(t)$ and $b_m(t)$, thus to adapt the value of $\alpha(t)$ every ΔT seconds (where ΔT is a constant). If the quality of the wireless channel is assumed to be constant during a time frame, then $\Delta T = T_f$. Thus, the $[0,\ T]$ interval is divided in $K = \frac{T}{T_f}$ sub-intervals of T_f seconds: $[T_k, T_{k+1})$, $k \in \{0, 1, ..., K-1\}$, where $T_0 = 0$ and $T_K = T$, during each of which the value of the function $\alpha(t)$ is constant. The value of $\varphi(t)$ is by definition constant during all these time intervals.

1) Calculation of the loss rate: Let a_k, φ_k, η_k and b_{m_k} be the values of $a(t)$, $\varphi(t)$, $\eta(t)$ and $b_m(t)$, respectively, during the time interval $[T_k, T_{k+1})$. Similarly, $x_k = x(T_k)$ is the buffer load at T_k and $L_k = \int_{T_k}^{T_{k+1}} \lambda(\tau)\, d\tau$ is the overflow volume during $[T_k, T_{k+1})$. The buffer load at T_{k+1} is

$$x_{k+1} = min\left\{max\left\{x_k + [\alpha_k - \varphi_k] \cdot T_f,\ 0\right\},\ C\right\}, \quad (2)$$

while the overflow volume during $[T_k, T_{k+1})$ is

$$L_k = \begin{cases} [\alpha_k - \varphi_k] \cdot T_f + x_k - C, & \text{if } x_{k+1} = C \\ 0, & \text{else} \end{cases}.$$

Thus, in $[T_k, T_{k+1})$ the overflow rate is $R_{overflow,k} = \frac{L_k}{\alpha_k \cdot T_f}$. The error rate during $[T_k, T_{k+1})$, assuming constant wireless channel quality during a time frame, is $R_{err,k} = 1 - (1 - BER_k)^{b_{m_k}}$ where BER_k is the connection BER during the time frame.

Finally, the total loss rate during $[T_k, T_{k+1})$, according to which the decision algorithm will instruct for proper adaptations of the modulation order or the encoding mode, is as follows:

$$\begin{aligned} R_{loss,k} &= R_{overflow,k} + R_{err,k} \cdot (1 - R_{overflow,k}) \\ &= \frac{L_k}{\alpha_k \cdot T_f} + \left(1 - (1 - BER_k)^{b_{m_k}}\right) \cdot \left(1 - \frac{L_k}{\alpha_k \cdot T_f}\right). \end{aligned} \quad (3)$$

2) Calculation of the mean delay: The value of the data source mean delay, $\bar{S}_k$, during $[T_k, T_{k+1})$ is derived from the mean buffer load (given the constant service rate of the queue). More specifically, in the time interval $[T_k, T_{k+1})$ the mean buffer load is $\bar{x}_k = \frac{1}{T_f}\int_{T_k}^{T_{k+1}} x_k(\tau)\,d\tau$. Thus, for the mean delay we have $\bar{S}_k = \bar{x}_k \cdot \frac{T_f}{c}$.

D. Wireless Channel Model

To model how the BER affects the data source loss rate we need a more specific wireless channel model. The connection is assumed to have a constant mean SNR value, denoted by $\bar{\gamma}$. According to [7], the instantaneous SNR, referred to as γ, is statistically described by the Nakagami-m channel model. According to this model, γ is a random variable following the Gamma distribution with probability density function (pdf) $p_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} exp\left(-\frac{m\gamma}{\bar{\gamma}}\right)$ where $\Gamma(m) = \int_0^\infty t^{m-1} exp(-t)\,dt$ is the Gamma function, and m is the fading parameter of the Nakagami-m channel model, $m \geq 1/2$. In this paper, we use $m = 1$, i.e., we assume a Rayleigh fading wireless channel.

IV. System Model

Consider a single source CFM, with the source generating data with encoding rate $\mu_d(t)$ bits/s and modulation order $b_m(t)$ bits/symbol. The maximum tolerable loss rate is ε_{max} while the maximum tolerable waiting time in the buffer is S_{max}. The δ parameter, which is used by the decision algorithm and is the basic criterion for the determination of the most appropriate modulation order and encoding mode, is defined as the ratio of the error rate over the total loss rate: $\delta = \frac{R_{err}}{R_{loss}}$.

This single source system can be modeled as a Markov chain whose state is the triplet (d, m, x), where d is the encoding mode, m is the modulation order, and x is the discretized buffer load. For the state space E of this chain we have $E = \{(d, m, x)\colon d \in \{1, 2, ..., D\},\ m \in \{1, 2, ..., M\},\ x \in \{0, 1, ..., C\}\ \}$.

This model can be extended to a symmetric multiple source system as follows. Consider N identical data sources of the same traffic class. If the size of the queue equals C symbols, it can be assumed that $\frac{C}{N}$ symbols are dedicated to each source. Each source is then modeled as an independent Markov chain of $D \times M \times (\frac{C}{N} + 1)$ states.

A. Calculation of the Markov Chain transition probabilities

Since adaptations of the modulation order and the encoding mode are only allowed between successive levels, we have

$$P((d, m, x), (d', m', x')) = 0, \text{ if } |d - d'| > 1 \text{ or } |m - m'| > 1.$$

According to the CLEMA decision algorithm, the state transitions occur as follows:

1) Transition to a state with *lower modulation order*:

$$\begin{aligned} & P((d, m, x), (d, m-1, x')) \\ = \;& P(R_{loss} > \varepsilon_{max},\ \delta > \delta_{med}),\ m > 1, \end{aligned}$$

where x' is the buffer load after the transition to the new state.

2) Transition to a state with *higher modulation order*:

$$\begin{aligned} & P((d, m, x), (d, m+1, x')) \\ = \;& P\Big(R_{loss} > \varepsilon_{max}, \delta < \delta_{low} \\ & \cup\ R_{loss} < \varepsilon_{min}, \frac{\bar{S}}{S_{max}} > \beta\Big),\ m < M. \end{aligned}$$

3) Transition to a state with *lower encoding mode*:

$$\begin{aligned} & P((d, m, x), (d-1, m, x')) \\ = \;& P(R_{loss} > \varepsilon_{max},\ \delta_{low} < \delta < \delta_{med}),\ d > 1. \end{aligned}$$

4) Transition to a state with *higher encoding mode*:

$$\begin{aligned} & P((d, m, x), (d+1, m, x')) \\ = \;& P\left(R_{loss} < \varepsilon_{min},\ \frac{\bar{S}}{S_{max}} < \beta\right),\ d < D. \end{aligned}$$

In any other case, only transition from state (d, m, x) to state (d, m, x') occurs.

Using the previously described CFM, the probability of transition to a state with lower modulation order, i.e., $(d_i, m_i, x_i) \rightarrow (d_i, m_i - 1, x_j)$, $m_i > 1$, $i, j \in E$ can be calculated. According to (2), $x_j = min\left(max\left(x_i' + \left(\frac{\mu_{d_i}}{b_{m_i-1}} - \varphi\right) \cdot T_f,\ 0\right),\ C\right)$ and $x_i' = min\left(x_i \cdot \frac{b_{m_i}}{b_{m_i-1}},\ C\right)$.

The probability of this transition is

$$\begin{aligned} & P(i,j) = P(R_{loss} > \varepsilon_{max},\ \delta > \delta_{med}) \\ = \;& P\Bigg(\left(\frac{L_i}{\alpha_i \cdot T_f} + \left(1 - (1 - BER_i)^{b_{m_i}}\right) \cdot \left(1 - \frac{L_i}{\alpha_i \cdot T_f}\right)\right) > \varepsilon_{max}, \\ & \frac{1 - (1 - BER_i)^{b_{m_i}}}{\frac{L_i}{\alpha_i \cdot T_f} + \left(1 - (1 - BER_i)^{b_{m_i}}\right) \cdot \left(1 - \frac{L_i}{\alpha_i \cdot T_f}\right)} > \delta_{med}\Bigg) \\ = \;& P\Bigg(BER_i > 1 - \left(\frac{1 - \varepsilon_{max}}{1 - \frac{L_i}{\alpha_i \cdot T_f}}\right)^{\frac{1}{b_{m_i}}}, \\ & BER_i > 1 - \left(1 - \frac{\frac{L_i}{\alpha_i \cdot T_f} \cdot \delta_{med}}{1 - \delta_{med} \cdot \left(1 - \frac{L_i}{\alpha_i \cdot T_f}\right)}\right)^{\frac{1}{b_{m_i}}}\Bigg) \\ = \;& P\Bigg(BER_i > max\Bigg\{1 - \left(\frac{1 - \varepsilon_{max}}{1 - \frac{L_i}{\alpha_i \cdot T_f}}\right)^{\frac{1}{b_{m_i}}}, \\ & 1 - \left(1 - \frac{\frac{L_i}{\alpha_i \cdot T_f} \cdot \delta_{med}}{1 - \delta_{med} \cdot \left(1 - \frac{L_i}{\alpha_i \cdot T_f}\right)}\right)^{\frac{1}{b_{m_i}}}\Bigg\}\Bigg). \end{aligned}$$

The probabilities of all other possible transitions are derived in a similar way.

B. Calculation of the mean system loss

To evaluate the performance of the system that employs the CLEMA mechanism, the mean overflow and the mean error rate have to be calculated. Let the values of the thresholds δ_{low}, δ_{med} and β be such that the Markov chain does not contain any absorbing states, and let E_c be its minimum closed set. Since E_c has a finite number of states, the system $\pi P = \pi,\ \pi\mathbf{1} = \mathbf{1}$, where P is the transition matrix of E_c, has a strictly unique solution and $\pi(j) = \lim_{n\to\infty} P^n(i, j),\ \forall\ i, j \in E_c$ [8].

For the system mean loss rate we have $R_{loss} = \sum_{i \in E_c} \pi(i) \cdot R_{loss,i}$ where $R_{loss,i} = R_{overflow,i} + R_{err,i} \cdot (1 - R_{overflow,i})$ is the loss rate in state i, according to (3).

Let the system be in state $i \in E_c$, with inflow rate α_i symbols/s, modulation order b_{m_i} bits/symbol, overflow volume L_i symbols, buffer load x_i symbols, and mean bit error rate $BER_i = f(\bar{\gamma}_i, b_{m_i})$.

Apart from the loss that is a result of overflow due to excess inflow rate, additional overflow can occur in case the system performs a transition to a state with lower modulation order. More specifically, due to the fact that the decrease of the modulation order results in an increase of the buffer load, it is possible that overflow occurs due to such a transition. This loss is calculated for transitions to state $i \in E_c$ from each state $j \in E_c$ such that $j \neq i$, $b_{m_j} > b_{m_i}$, and is equal to $L_{transition}(j,i) = max\left(x_j \frac{b_{m_j}}{b_{m_i}} - C,\ 0\right)$. Thus, the total data loss (in bits) in state i due to overflow, which is the result of modulation order decreases, is $L_{transition}(i) = \sum_{j \in E_c,\ b_{m_j} > b_{m_i}} P(j,i) \cdot L_{transition}(j,i) \cdot b_{m_i}$. Thus, the system mean loss volume due to overflow caused by modulation order decreases is $L_{transition} = \sum_{i \in E_c} L_{transition}(i) \cdot \pi(i)$.

C. The Legacy System

The performance of the system employing CLEMA is compared against a typical system, referred to as "legacy" system, which performs the operations of adaptive modulation and encoding mode adjustment separately and independently of each other. More specifically, in the legacy system a decrease of the modulation order is performed if the current value of the BER is higher than the maximum tolerable BER, BER_{max}, while an increase of the modulation order is performed if the BER is lower than the minimum BER, BER_{min}. Similarly, a transition to a state with lower encoding mode is performed if the total loss rate exceeds the maximum tolerable loss rate ε_{max}, while a transition to a state with higher encoding mode is performed if the loss rate is lower than ε_{min}. The modeling of the legacy system is analogous to that of the system that employs CLEMA using a CFM, while a data source is modeled as a Markov chain of $D \times M \times (C+1)$ states. Using a similar methodology, the transition probabilities between the various states of the Markov chain that models the legacy system can be calculated, and the mean delay as well as the additional losses caused by modulation order adaptations can be derived.

D. Derivation of the optimal adaptation thresholds

The optimal values $\delta_{low_{opt}}$, $\delta_{med_{opt}}$, and β_{opt} of the thresholds δ_{low}, δ_{med} and β, used by the CLEMA decision algorithm are the ones that minimize the system loss rate R_{loss}, while maintaining the system's mean error rate $R_{err_{CLEMA}}$ lower than or at most equal to the error rate of the respective legacy system $R_{err_{Leg}}$.

V. Performance Evaluation

With the use of Matlab, the performance of the system employing CLEMA with optimal values of the thresholds δ_{low}, δ_{med} and β (referred to as "optimal CLEMA") was compared against i) the legacy system, and ii) a system that employs CLEMA with constant sub-optimal values of the adaptation thresholds (referred to as "sub-optimal CLEMA"). The performance metrics used for the comparison of the three systems were the mean loss rate R_{loss}, and the mean delay $\bar{S}$.

The evaluation scenario considers a data source that produces Adaptive Multi-Rate (AMR) [9] voice traffic with five discrete encoding modes. The modulation orders used are QPSK, 16-QAM and 64-QAM, which correspond to 2, 4 and 6 bits/symbol, respectively. The duration of the MAC layer time frame, which is the period used for the adaptation decisions, is 5 ms. The maximum tolerable waiting time in the queue S_{max} is 40 ms. The maximum tolerable loss rate ε_{max} is equal to $7 \cdot 10^{-3}$, while the value of ε_{min} is 10^{-9}. The values of the thresholds based on which the legacy system performs the adaptations of the modulation order are: $BER_{max} = 10^{-6}$ and $BER_{min} = 10^{-9}$.

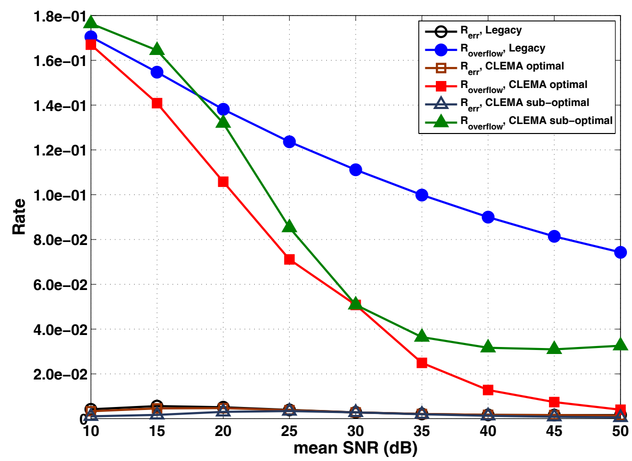

Fig. 4. R_{err} and $R_{overflow}$ vs. $\bar{\gamma}$

Figure 4 depicts the mean overflow rate, $R_{overflow}$, and the mean error rate R_{err} of the three systems (optimal CLEMA, sub-optimal CLEMA and legacy) versus the mean SNR ($\bar{\gamma}$) of the data source. The service rate per traffic frame equals $c = 10$ symbols/5 ms, which corresponds to a queue size of $C = 80$ symbols. All three systems manage to maintain a relatively low mean error rate, which generally decreases as the mean SNR increases. This is a result of the fact that, as the conditions of the wireless medium improve, the systems have the ability to increase the system data rate by instructing more frequent transitions to states with higher modulation orders. Nevertheless, the legacy system is characterized by a relatively high overflow rate, as a result of the independent operation of the adaptive modulation at the Physical layer and the encoding mode adaptations at the Application layer. On the contrary, optimal CLEMA results in a significantly lower overflow rate, especially in cases of increased mean SNR, taking advantage of the coordinated operation and the optimal values.

The importance of the dynamic adaptation of the values of the thresholds δ_{low}, δ_{med} and β is depicted from the performance of sub-optimal CLEMA, whose threshold values are constant and optimal only for the case of $\bar{\gamma}$=30 dB, as shown in Figure 4. Although this system results in improved performance compared to the legacy system, it does not manage to obtain the minimum values of the mean overflow rate of optimal CLEMA for all values of the mean SNR.

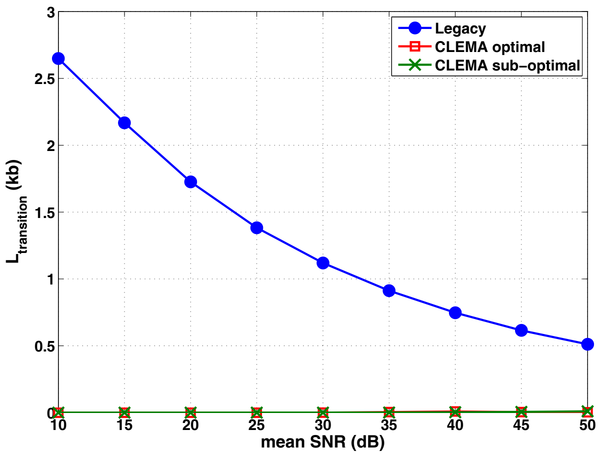

Fig. 5. $L_{transition}$ vs. $\bar{\gamma}$ (service rate per traffic frame c=10 symbols/5ms)

Figure 5 depicts the data loss $L_{transition}$ of the legacy, optimal CLEMA and sub-optimal CLEMA systems caused by transitions in states with lower modulation order that, depending on the queue load, may result in data overflow. In the three systems under consideration, $L_{transition}$ follows a declining course as the mean SNR increases. This is a result of the fact that, as the quality of the wireless medium improves, transitions to states with lower modulation orders are instructed less frequently. Thus, in such cases, the volume of the data loss is lower. As shown in this figure, the operation of adaptive modulation in the legacy system, which is performed based exclusively on the mean SNR, leads to more frequent reductions of the modulation order compared to the systems that employ the optimal and sub-optimal CLEMA mechanisms, resulting in significantly higher data loss. Both optimal and sub-optimal CLEMA have similar and significantly improved performance in terms of additional data losses compared to the legacy system, as this depends mainly on the operation of the CLEMA decision algorithm.

Figure 6 plots the mean delay versus the mean SNR for the three systems under comparison. Clearly, optimal CLEMA has significantly improved performance in terms of mean delay compared to the legacy and sub-optimal CLEMA systems, especially in cases of favorable wireless channel conditions.

Finally, Figure 7 depicts the total loss rate of the legacy system and the system employing the CLEMA mechanism as a function of the thresholds δ_{low} and δ_{med}, assuming a mean SNR equal to 20 dB, and a service rate per traffic frame c=20 symbols/5ms, which corresponds to a queue size of $C = 160$ symbols. Additionally, for the CLEMA mechanism the value

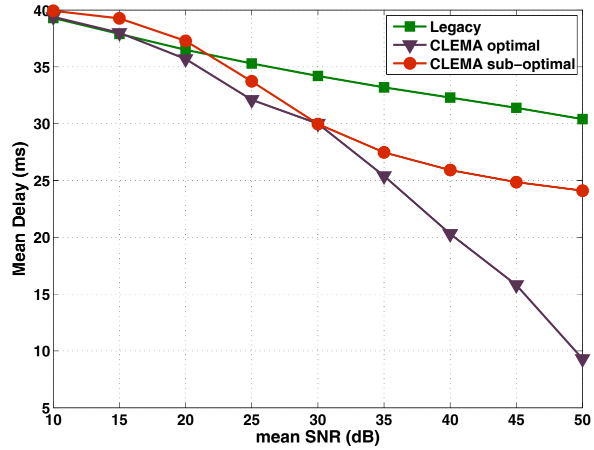

Fig. 6. Mean delay vs. $\bar{\gamma}$

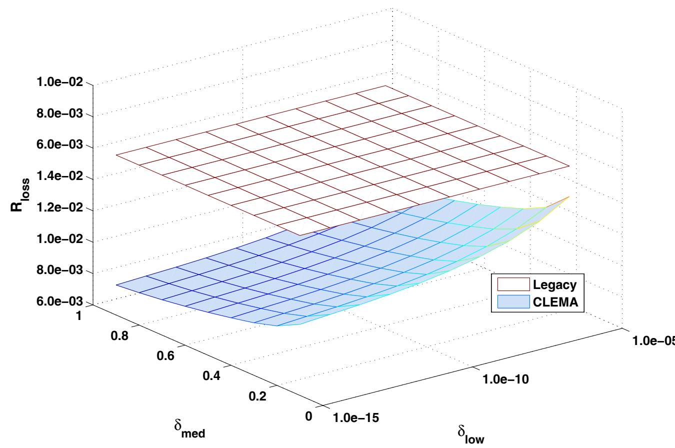

Fig. 7. R_{loss} vs. the values of δ_{low} and δ_{med}

of the threshold β equals 0.3. As expected, the loss rate of the legacy system has a constant value of $1.21 \cdot 10^{-2}$, as its performance is not affected by the values of the thresholds. On the contrary, the loss rate of CLEMA decreases as the value of δ_{low} decreases and the value of δ_{med} increases, with the optimal performance obtained when δ_{low}=0 and δ_{med}=1. This means that, in this case, optimal CLEMA instructs an increase of the modulation order only when no errors occur at the wireless channel, and a decrease of the modulation order only when the queue experiences no overflow.

VI. Conclusions

In this paper, we have introduced a Continuous Flow Model for the analysis and optimization of the CLEMA mechanism proposed in [3]. The model consists of a “fluid” queue whose inflow and outflow rates represent the system’s traffic generation and service rates, respectively. Each data source is modeled as a discrete-time Markov chain, with each state representing its current encoding mode, modulation order and respective buffer load. The Markov chain's transition probabilities are derived from the CLEMA decision algorithm. The system performance is assessed in terms of overflow rate, error rate and mean delay. Performance evaluation results show that CLEMA with the optimal values for the adaptation thresholds, derived by the proposed CFM, significantly outperforms both a legacy system that performs the adaptations of the modulation order and encoding mode separately and independently of each other, and a system employing sub-optimal CLEMA using static values of its adaptation thresholds.

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