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Predicting Multimedia Traffic in Wireless Networks: A Performance Evaluation of Cognitive Techniques

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Abstract—Traffic engineering in networking is defined as the process that incorporates sophisticated methods in order to ensure optimization and high network performance. One of the most constructive tools employed by the traffic engineering concept is the traffic prediction. Having in mind the heterogeneous traffic patterns originated by various modern services and network platforms, the need of a robust, cognitive, and error-free prediction technique becomes even more pressing. This work focuses on the prediction concept as an autonomous, functional, and efficient process, where multiple cutting-edge methods are presented, modeled, and thoroughly assessed. To this purpose, real traffic traces have been captured, including multiple multimedia traffic flows, so as to comparatively assess widely used methods in terms of accuracy.

Keywords—extrapolation; automata; markov chains; prediction; wireless networks;

I. INTRODUCTION

Modern services and applications require a robust network framework, including many intelligent, cognitive, and sophisticated processes and procedures, in order to reach the maximum of their capabilities. Latest wireless standards incorporate intelligent functionality, dynamic allocation, and expanded control; however they entail an efficient supportive suite of surrounded protocols and algorithms. For instance, semi-persistent scheduling in Long Term Evolution (LTE) networks involves dynamic scheduling in allocating burst grants in voice packet transmission. Moreover, traffic engineering emerges as a beneficial and supportive framework towards ensuring high levels of network performance. Among others, traffic engineering adopts prediction/estimation techniques in order to provide various decision processes with complete or insightful picture on critical information. Multitude prediction tools have been developed for providing forecasting in wireless networks [1], cognitive networks [2], and wired networks, such as optical networking [3].

In general, a prediction tool is used to forecast a sequence of time series. In the context of wireless networking, the values represented by the series may be attached to various performance parameters such as a) packet size. b) interarrival time, c) number of users, d) duration of a sleeping period, e) burstiness, and f) signal or noise levels. In essence, by

applying a prediction process an a priori knowledge is obtained regarding a specific network parameter. For example, by forecasting the packet size and the interarrival time of users' traffic requests the efficacy of the computed decisions could be thoroughly improved even totally optimized if the prediction process is quite accurate. In wireless environments, where the main goals are the low user's perceived latency, due to application sensitivity, and the high channel utilization, due to bandwidth limitations, the utilization of a rigorous prediction tool could be extremely beneficial. In this way, modern wireless networks could cope with the proliferation of cellular network, accompanied with the vast growth of users involved, as well as the fast penetration of bandwidth-demanding Internet services.

Following the definition given in [4], traffic prediction is the task of retrieving the past traffic requests in deducing what the future bandwidth requests will be. Accordingly, traffic prediction can positively affect the network performance by allowing more efficient decisions. For example, in a time instance, a decision component can allocate surplus bandwidth from users that will not use it to users that really need it if it is aware of users' bandwidth requests in advance. Thus, the channel utilization is improved since the wasted bandwidth, due to idle/inactive users, is properly exploited and user latency is reduced due to the fact that the bandwidth requests of active users are faster satisfied. However, the applied prediction method is necessary to be accurate enough inducing low error rate. It is obvious that an inefficient traffic estimation could lead to performance impairments such as unfair schedule, under-utilization, and high delays.

In this work, the cognitive capabilities of several cutting-edge prediction methods are identified. In order to stimulate the solidity of our research, we apply these methods to real traffic traces obtained from a Worldwide Interoperability for Microwave Access (WiMAX) infrastructure. Yet, the obtained traces belong to various multimedia flows such as Voice over IP (VoIP) and live streaming, offering even more credibility in our research findings. The contributions of this work are summarized as follows:

- It presents the most popular, efficient, and effective prediction tools focused on the traffic prediction.

- It thoroughly assesses the prediction tools in terms of accuracy and effectiveness.
- It incorporates a real-time prediction framework by using real traffic traces captured during actual multimedia data delivery.
- It identifies each tool's merits and inefficiencies. Furthermore, it infers about the most applicable prediction tool regarding multimedia traffic of a broadband wireless network.

The remainder of this paper is organized as follows. Section III describes the adopted prediction tools in detail, while Section II outlines previous work in communication networks. Section IV presents evaluation results accompanied by detailed comments. Finally, Section V concludes this paper.

II. RELATED WORK

Considering modern communication networks and protocols, three of the most popular and effective cognitive prediction tools are a) interpolation and extrapolation, b) Markov chains, and c) learning automata (LAs).

Interpolation and extrapolation methods are quite popular in approximating unknown functions. Furthermore, they are employed to dynamically determine the most appropriate downlink-to-uplink width ratio in accordance to traffic demands in WiMAX systems [5], facilitate the spectrum access in cognitive radio networks [6], estimate channel characteristics in Multi-User Multiple Input Multiple Output (MU-MIMO) systems [7], and approximate the item demand probability distribution function in wireless push systems [8].

LAs have found use in communication networks, especially in wireless networking. In underwater acoustic wireless networks the authors in [9] investigate the data dissemination and the high latency problem by enhancing an adaptive push system with a LA component. A paradigm of developing traffic engineering using LA can be found in [10]. Lastly, in [11] the BaseStation (BS) of a WiMAX access network is strengthened by utilizing a LA in order to improve the bandwidth allocation process.

Models built by Markov chains are quite popular in communication and networking. In [12] a framework that performs Quality of Experience (QoE) estimation and prediction using passive probing mechanisms is presented, while in [3] a Hidden Markov Chain (HMC) is designed to predict individual Quality of Service (QoS) features is suggested. The authors in [13] introduced a Markov renewal process for both mobility modeling and predicting in wireless networks. The work in [14] inaugurates an efficient content sharing scheme for smartphone networks. Lastly, a new algorithm for predicting audio packet playout delay for VoIP conferencing applications is implemented in [15].

III. PREDICTION TOOLS

A. Extrapolation Techniques

Both interpolation and extrapolation methods are quite popular on fitting smooth continuous functions through discrete data. Interpolation uses actual scattered data to estimate

unknown values between the lower and the upper value of the actual set. On the other hand, extrapolation estimates values beyond the limits of the actual set. For example, assuming that for the time series of $x = [1.2, 2.3, 3.7, 4.3, 5.5]$ the values of function F are $F = [5.2, 4.6, 3.4, 2.1, 0.5]$, the aim of interpolation is to estimate the value of F given that $1.2 \leq x \leq 5.5$, e.g., the value of $F(3.9)$. On the contrary, the extrapolation technique intends to predict the F value when $x > 5.5$ or $x < 1.2$, e.g., the value of $F(6.1)$.

In the context of traffic prediction the extrapolation method is functional since it allows the prediction of future values in advance. Among other interesting extrapolation techniques, the *Lagrangian Polynomials* and the *Spline Curves* are the most attractive ones.

Maybe the most straightforward way to extrapolate data is the *Lagrangian Polynomials*. Given a set of historical data, the method of *Lagrangian Polynomials* forms a sum of polynomials in order to fit the unknown function that generated the actual (historical) data. Consider an actual set of $F(x_1), F(x_2), \dots, F(x_n)$ values for a given set of x values, x_1, x_2, \dots, x_n . These values are real and have been measured in the context of an experiment. The *Lagrangian Polynomial* forms the polynomial $R(x)$ aiming at fitting the unknown function F , where $R(x) = \sum_{j=1}^n R_j(x)$. The function $R_j(x)$ is further defined as $R_j(x) = F(x_j) \prod_{k=1, k \neq j}^n \frac{x-x_k}{x_j-x_k}$. It is obvious that the estimated polynomial $R(x)$ passes through the known values trying to extend the form of the estimated function F . In addition, the polynomial $R(x)$ has a degree of at most $n - 1$.

Polynomials of high degrees may present great deviations resulting in high estimation error. *Spline Curves*, or simply *Splines*, constitute piecewise polynomial functions that combine simplicity, in terms of computing parameters, and flexibility, in terms of smoothness and easiness on handling arbitrary functions. In essence, *Splines* are piecewise polynomials with pieces that are smoothly connected together.

One of the most interesting advantages of *Splines* is the low complexity, since they keep the computational requirements low compared to other interpolation techniques that include complex numerical calculations, involving higher degree curves. The *Cubic Spline* is further popular, since it offers minimum curvature property, high-quality fitting, simple representation, and smoothness.

Given a set of $n+1$ knots, that is historical (actual) values, each pair of successive knots $(x_j, x_{j+1}), j = [1, 2, \dots, n, n+1]$, corresponding to $F(x_j), F(x_{j+1})$, defines a *Spline*. This means that a Spline fits a set of n^{th} -degree polynomials between each pair of knots. The approximation function $S(x)$ is defined as follows:

$$S(x) = \begin{cases} S_1(x) & \text{if } x_1 \leq x \leq x_2 \\ S_2(x) & \text{if } x_2 \leq x \leq x_3 \\ \dots & \dots \\ S_n(x) & \text{if } x_n \leq x \leq x_{n+1} \end{cases} \quad (1)$$

The $S_j(x)$ denotes a third (cubic) degree polynomial between the j^{th} knot, that is $(x_j, x_{j+1}), j = [1, 2, \dots, n]$. It has the following form:

$$S_j(x) = a_j(x - x_j)^3 + b_j(x - x_j)^2 + c_j(x - x_j) + d_j \quad (2)$$

The a_j, b_j, c_j and d_j parameters are determined as follows:

$$a_j = \frac{S_{j+1} - S_j}{6(x - x_{j+1})}, b_j = \frac{S_j}{2}$$

$$c_j = \frac{F(x_{j+1}) - F(x_j)}{(x - x_{j+1})} - \frac{2(x - x_{j+1})S_j + (x - x_{j+1})S_{j+1}}{6}$$

$$d_j = F(x_j)$$

Both *Lagrangian Polynomial* and *Cubic Spline* techniques are incorporated and assessed in this work. The function of the extrapolation techniques in order to be able to predict network traffic is modeled as follows. The time domain is divided into discrete time instances, $T = [0, 1, \dots]$. Each arrival represents a time instance, i.e., the first arrival triggers time instance $T = 0$, the second happens in $T = 1$ etc. On the one hand, each arrival generates an integer value corresponding the data packet size in [64, 1518], in terms of Bytes, since an Ethernet network is considered. Hence, the extrapolation intends to predict the (next) packet size at time $T = t_{n+1}$, known the actual values of all previous arrivals $0 \leq T \leq t_n$. In other words, the extrapolation method tries to estimate the actual value of $F^{size}(x_{t_{n+1}})$, i.e., actual packet size, by forming the polynomials $R_{t_{n+1}}^{size}(x)$ and $S_{t_{n+1}}^{size}(x)$ for *Lagrangian Polynomials* and *Splines* respectively. In a similar way, the estimation of the (next) arrival time in sec follows the same structure in time domain; however the polynomials $R_{t_{n+1}}^{time}(x)$ and $S_{t_{n+1}}^{time}(x)$ indicate (arrival) time values based on the (arrival) times of the past given by the actual function $F^{time}(x_{t_{n+1}})$.

B. Markov Chains

Markov processes provide very flexible, powerful, and efficient means for the description and analysis of dynamic (computer) system properties. Markov processes constitute a special subclass of stochastic processes. In particular, a stochastic process provides a relation between the elements of a possibly infinite family of random variables. A series of random experiments can thus be taken into consideration and analyzed as a whole [16].

Considering a number of n observations obtained from an experiment, an actual set of $F(x_1), F(x_2), \dots, F(x_n)$ values for a given set of x values, x_1, x_2, \dots, x_n is defined. In general, a stochastic process, X_t is defined as a set of random variables in the time domain, $t \in T$, where $T \subseteq \mathbb{R}_+ = [0, \infty]$. Taking into account that our objective is to predict the (future) values of F , the problem is formulated in estimating the values of X_t when $t > t_{current}$ where $t_{current}$ is the current time instance.

The stochastic process incorporates a state space B which represents the set of all possible values of X_t . In our case, the state space B represents all possible values of the underlying function F . In addition, we consider a countable time parameter T resulting in a discrete-parameter process, thus T obeys to \mathbb{N}_0 . For instance, if $F(x)$ generates the number of users connected to a wireless BS at time x , then $F(x) \in [0, n]$, where

n is the maximum accepted number of users in the BS. The state space B in this case is defined as $B = [B_1, B_2, \dots, B_n]$ indicating the number of connected users as a distinct state.

In the light of the aforementioned observations, a stochastic process X_t defines a Markov process if for all $t, t_1 < t_2 < \dots < t_n$ and all states of B the $X_{t_{n+1}}$ depends only on the last value X_{t_n} and not on the earlier values:

$$P(X_{t_{n+1}} \leq B_{n+1} | X_{t_n} = B_n) \quad (3)$$

In predicting the packet size, each state corresponds to all possible values, i.e., $B^{size} = [64, 65, \dots, 1518]$. However, predicting (arrival) times is not straightforward, because the actual values are real numbers. To remedy this difficulty, we normalize the allowable arrival times in equally divided spaces of 0.2 sec. Hence, $B^{time} = [0.2, 0.4, \dots]$. For each time instance t , the actual state is denoted as q_t^{size} (q_t^{time}). Since each state corresponds to a specific observation notation, the specifications and the observation features, $O_t^{size/time}$, are defined below:

$$P(O_t^{size} = k_z^{size} | q_t^{size} = B_z^{size}) \quad (4)$$

$$P(O_t^{time} = k_y^{time} | q_t^{time} = B_y^{time}) \quad (5)$$

where $1 \leq z \leq 1455$, $1 \leq y \leq 301$, while $k_1^{size} = 64, k_2^{size} = 65, \dots, k_{1455}^{size} = 1518$, and $k_1^{time} = 0.2, k_2^{time} = 0.4, \dots, k_{301}^{time} > 60$. The special value of k_{301}^{size} is associated with (arrival) time values larger than 1 min. The state transition probability distribution is described by the following equation:

$$a_{i,j}^{size} = P[q_{t'}^{size} = B_j^{size} | q_t^{size} = B_i^{size}] \quad (6)$$

$$a_{m,n}^{time} = P[q_{t'}^{time} = B_j^{time} | q_t^{time} = B_i^{time}] \quad (7)$$

where $1 \leq i, j \leq 1455$ and $1 \leq m, n \leq 301$. $a_{i,j}^{size}$ ($a_{m,n}^{time}$) denotes the transition probability from state i (m) to state j (n), and i, j (m, n) symbolize the length of the packet arrived (arrival time) at (between) t and t' , respectively, while t' denotes the next time instance. Each state stores the number transitions for all other states. Finally, the most frequent transition from the actual one is selected by the prediction model as the next (estimated) action.

C. Learning Automata

LAs are artificial intelligence tools that can provide adaptation to systems operating in changing and/or unknown environments. A LA is a finite state machine that interacts with a stochastic environment and tries to learn the optimal action offered by the environment via a learning process. There is a bidirectional information exchange between the environment and the LA module. First, a specific action is chosen by the LA from a pool of allowable actions. Second, a reaction is emerged by the environment resulting in a feedback. The feedback is received by the LA and it is appropriately processed so as to compute the next action to perform. The goal for the LA is to choose the best possible action from the allowable ones. One

of the major merits the LAs exhibit is their low computational complexity.

An LA continuously interacts with the random operating environment so as to find among a set of actions the one that minimizes the average penalty the system receives by the environment [17]. Assuming a set of n allowable actions, $e(1), e(2), \dots, e(n)$ this process can be modeled considering a probability distribution vector, $L_i, i = 1, 2, \dots, n$, which keeps and calculates the probability of each action $e(j)$. In order to preserve model's consistency, it holds that $\sum_{i=1}^n L_i = 1$.

The operation of predicting is based on a specific process which is incorporated by the prediction module. This process is called probability updating algorithm and its functionality is inherited by the features of the reinforcement learning. The time is divided into cycles (time instances), where the LA in each cycle t utilizes the feedback received by the environment in the previous cycle $t - 1$ to perform a prediction concerning the next cycle $t + 1$. Upon performing the prediction, the LA receives (again) a feedback, as a result of the action performed, which is used in order to update the probability distribution vector. In general, the probability of the actual action is favored, while all others are slightly reduced. To this end, the optimal action is distinguished from the action set by emerging as the most probable, and therefore preferable, action to the environment.

The probability updating algorithm may have multiple versions according to the subtle features of the environment. For example, the Linear Reward-Penalty (LR-P) scheme could be followed, where the LA selects an action from the pool and, after reception of a favorable response for the action that was selected, the corresponding probability of selecting this action again is increased, whereas after reception of an unfavorable response the probability of selecting this action again is decreased. On the other hand, the Linear Reward-Inaction (LR-I) scheme involves inaction upon the reception of an unfavorable response regarding the probability of the selected action. In this paper, the LR-I scheme is adopted and the update algorithm is structured as follows, where $e(o), 1 \leq o \leq n$ denotes the action the environment responds:

$$L_i(t+1) = L_i(t) - V(L_i(t) - u), \forall e(i) \neq e(o) \quad (8)$$

$$L_i(t+1) = L_i(t) + V \sum_{i \neq o} (L_i(t) - u), \text{ if } i = o \quad (9)$$

The V parameter constitutes the convergence rate of the learning process. A larger V leads to faster convergence since the update probability process is accelerated but causes higher fluctuation. The u parameter simply stands to avoid the probabilities from taking zero values. Hence, it usually receives a minimum value, e.g., 10^{-5} .

Here, the allowable actions $e^{size}(1), e^{size}(2), \dots, e^{size}(1455)$ and $e^{time}(1), e^{time}(2), \dots, e^{time}(301)$ denote all possible values of packet length, i.e., [64, 1518], and all possible (normalized) values if arrival time, i.e., [0.2, 60]. Initially, all probabilities, i.e., $L_i^{size}(L_i^{time})$ are received the initial value of $1/1455$ ($1/301$).

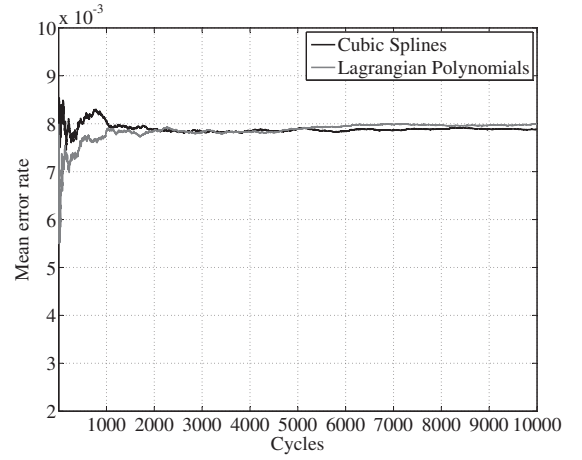


Fig. 1. Lagrangian Polynomials vs. Cubic Splines in terms of mean error rate.

IV. PERFORMANCE EVALUATION

1) *Environment*: In order to provide a robust evaluation environment, we engaged real WiMAX multimedia traffic traces stemming from a WiMAX access network during sessions between a BS and a Mobile Station (MS). The captured traffic corresponds to the downlink direction, i.e., the traffic delivered by the MS from the BS. The captured traffic streams were obtained using the Wireshark tool. Two traffic streams have been utilized: a) a VoIP session between a BS and a MS using the User Datagram Protocol (UDP) and the Skype application and b) a Real Media Streaming application based on Transmission Control Protocol (TCP). In each traffic stream two objectives are set, namely a) to predict the packet size in bytes and b) to predict the time of the next (packet) arrival (between two successive arrivals) in seconds. The simulator has been implemented in Matlab, while for each traffic stream three traffic parameters have been used: a) the packet serial number (ID), b) the packet size in Bytes, and c) the arrival time.

The assessment is based on accuracy in terms of mean error rate. In particular, the mean error rate is defined as follows:

$$E = \frac{|ActualValue - PredictedValue|}{TotalPossibleValues} \quad (10)$$

Concerning the VoIP application, the MS produced an average traffic of 0.038 Mbps, while the average packet size is equal to 1372 Bytes. The streaming application generated an average traffic of 0.04 Mbps having an average packet size of 121 Bytes. A number of 10000 samples, known as cycles, for both packet and interarrival time prediction has been retrieved. For each prediction tool a learning period is initiated, where the prediction module learns without providing output. The default value of the learning period duration is the 10% of the total cycles. Common values of V and u are 0.1 and 10^{-5} and these are adopted as default values for the present evaluation.

2) *Numerical Results*: First, the extrapolation method is assessed in terms of accuracy using as the captured data of the packet size originated from the streaming session. To be more specific, the *Lagrangian Polynomials* versus the *Cubic Splines*

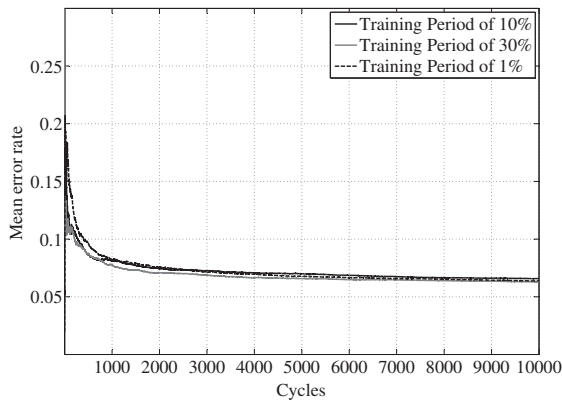


Fig. 2. Hidden Markov Chains evaluation in terms of training period.

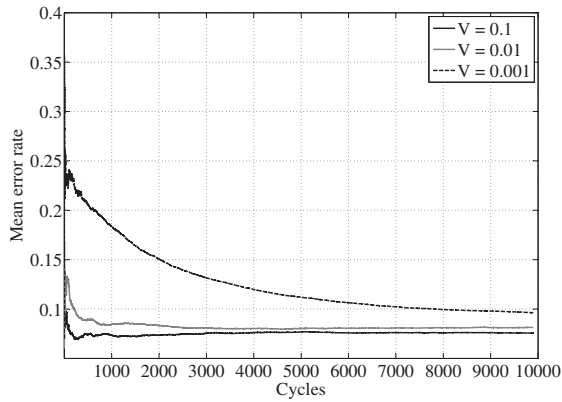


Fig. 3. Learning Automata evaluation in terms of convergence speed.

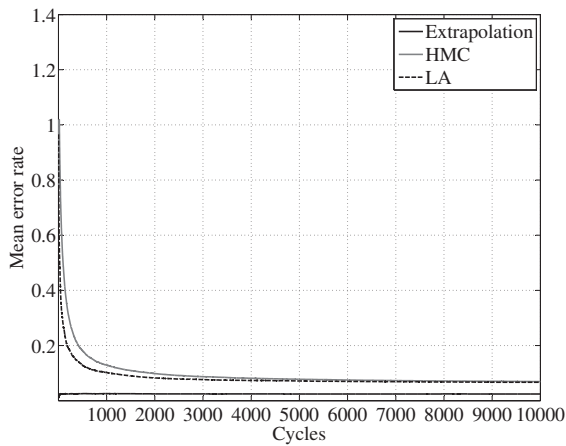


Fig. 4. Streaming session. Mean error rate on predicting the packet size in Bytes.

have been comparatively evaluated. Fig 1 depicts the results of this comparison. Initially both techniques experience high error rates due to the fact that the prediction process endeavors to learn the most frequent, and therefore, the appropriate packet size values. After 2000 cycles both techniques converge presenting an almost stable error rate of $8 \cdot 10^{-3}$. In general, similar accuracy is observed for both techniques. However, the *Cubic Splines* technique seems to offer slightly more accurate predictions, due to its ability to smoothly engaging polynomi-

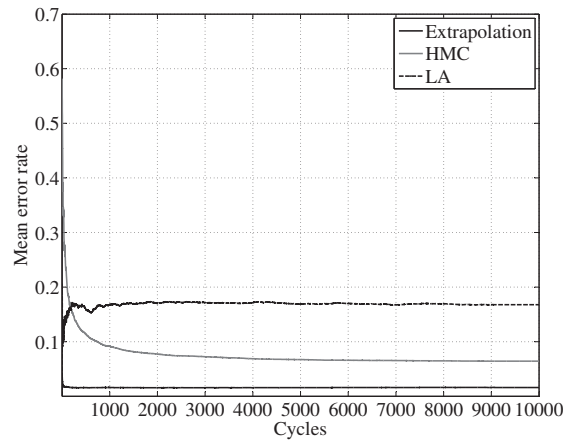


Fig. 5. Streaming session. Mean error rate on predicting the arrival time in sec.

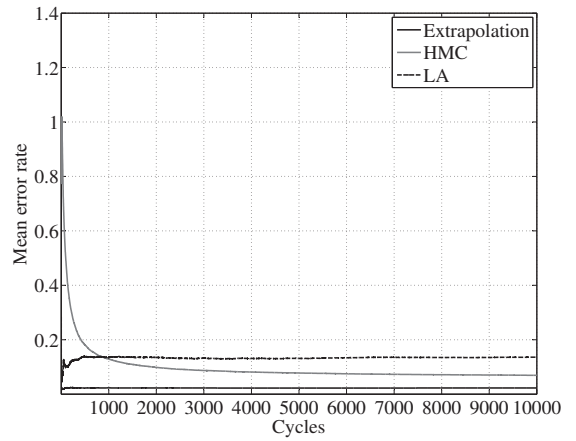


Fig. 6. VoIP session. Mean error rate on predicting the packet size in Bytes.

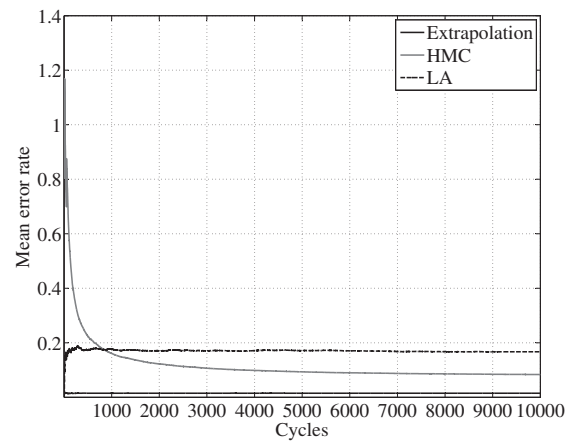


Fig. 7. VoIP session. Mean error rate on predicting the arrival time in sec.

als, hence it is indicated as the representative technique of the extrapolation method.

Second, the HMC prediction framework is investigated by changing the learning period. As previously mentioned, the learning period of each prediction module was set to 1000 cycles. In Fig 2 the results of the conducted simulations are

shown where the learning period takes three different values, i.e., 100, 1000, and 3000. Once more the captured data of the streaming session were utilized in terms of data packet size. The results do not reveal anything special regarding the performance of HMC. In any case, the error rate reaches 0.07 approximately, hence it can be deduced that HMC is quite well on predicting the length of data packets regarding a streaming session. Another aspect raised has to do with the learning capability of the HMC tool. Indeed, Markov chains are able to adapt fast in the environment, offering immediate positive results.

In Fig 3 the efficiency of the LA tool is inspected. Again, the set of packet size data of the streaming session was fed to the model. Here, the parameter under evaluation is the convergence speed V which determines the impact of the probability updating algorithm in Eq. (8). It is obvious that the value of $V = 0.1$ is the most effective one. This is attached to the fact that predicting data packet length is a job that could allow a fast convergence since identical data packets are often repeated, hence the prediction module has the potential to learn quickly.

The next two figures, namely Fig 4 and Fig 5 provide an evaluation comparison between all prediction tools when the data packet size and the arrival time is estimated respectively. As previously, a total of 10000 samples have been utilized. The default value of the learning period is 1000 cycles. Two major aspects are raised by observing the Fig 4: a) the extrapolation technique seems to be the most efficient and b) all methods offer low levels of error rate, i.e., below 10%. Maybe, the superiority of the extrapolation method is a combination of smooth fitting and good matching due to the nature of the data under prediction. Furthermore, the above observations are yet enhanced by noticing that both HMC and LA require some time to converge. Similar conclusions are drawn by examining the Fig 5. It is worth mentioning that the obtained error level of the extrapolation method is quite low, while it converges almost immediately. LA present the highest levels of error, fact that stems from its functional operation; it often changes its optimal decision.

Lastly, Fig 6 depicts the prediction results on estimating the data packet size using the VoIP session as input. Accordingly, in Fig 7 the arrival predictions are illustrated. The observation of these figures lead to three critical remarks. First, the extrapolation technique looks as the most promising one since it provides accurate predictions for both data packet size and arrival time. Thus, it is capable of adequately estimating the main parameters of a (multimedia) traffic flow. Second, the HMC tool presents a fair error rate, below 10%. Third, the use of the LA tool is deemed as good enough, however it fails to ensure quite precise estimations as the extrapolation techniques does. In a nutshell, the usage of the extrapolation tool is indicated for multimedia traffic estimations based on our findings.

V. CONCLUSION

Three heterogeneous, cognitive prediction frameworks were modeled, presented, and evaluated on the basis of multimedia traffic prediction. All techniques utilized, namely extrapolation, Markov chains, and learning automata, demonstrated

notable estimation capabilities on predicting critical traffic parameters such as the data packet length and the arrival time. Our findings indicated that the usage of the extrapolation technique seems the most effective due to its ability to offer smooth fitting and fast learning ability.

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