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Mathematical Bottom-to-Up Approach in Video Quality Estimation Based on PHY and MAC Parameters

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ABSTRACT This paper presents an extension of research scope of the relationship between quality of service (QoS) and quality of experience (QoE), which is based on contribution of lower open system interconnection layers, such as physical and media access control, in overall QoS/QoE paradigm. Degradations that inevitably occur in transmission channel are an important reason for appearance of QoS distortion and therefore low values of video quality. Various channel quality indicators (CQIs) relating to domain of communication channel can be used for notification of different interferences in the channel. In order to extend the relationship between QoS and QoE to the transmission channel, the paper proposed the mathematical model that used CQI to estimate values of QoS indicators by using statistical analysis. The model was also expanded by objective video quality metrics in order to evaluate QoE. Verification of the model was checked by experimental method with consideration of Internet protocol television (IPTV) service delivery in Digital Subscriber Line network.

INDEX TERMS Quality of service, IPTV, statistical analysis, QoS/QoE relation, multimedia communication.

I. INTRODUCTION

Increasing the use of multimedia services, such as IPTV (*Internet Protocol TeleVision*) [1], encourages service and network operators to consider and monitor Quality of user Experience. Definition of QoE (*Quality of Experience*) that was given in [2] is ‘‘the overall acceptability of an application or service, as perceived subjectively by the end-user’’. In addition, there are still few definitions that were given in [3] and [4]. In accordance with ITU [5], QoE should include all the effects which are introduced by a system into end-to-end communication. This can relate to a client, terminal, network, infrastructure, service or other telecommunication items. The complete user acceptability of a service, in addition to all communication factors, may be affected by its expectations and the context in which the service is consumed. When considering QoE, the researchers focused on two types of quality assessment, either subjective or objective. The subjective one can be carried out through several techniques and it requires the presence of the user, his independence and serviceability. MOS (*Mean Opinion Score*) is the most commonly used quantitative measure of subjective assessment, while beside this, there are also qualitative measures that were conducted with the use of surveying and crowdsourcing techniques [6], [7]. Objective video quality metrics approximate subjective assessments and use several methods that can be classified by the amount of available information about the original signal. Survey of objective testing and metrics is given in [8]. Full reference objective methods, such as PSNR (*Peak Signal to Noise Ratio*) or SSIM (*Structural Similarities*), evaluate differences between frames by comparing the original video against the received one. Reduced reference methods use available information about original video signal and compare them with the same information of received signal. No reference metrics assess video quality without knowledge of features of original signal using QoS/QoE correlations or spatial and time differences in received signals. Ulrich *et al.* [9] emphasize that human, system and context factors influence QoE. The most important factor for service and network providers are systematic ones and they include content-related, media-related (encoding, resolution, rate), network-related (bandwidth, delay and jitter) and device-related (screen resolution, display or size) parameters. These factors, especially media and network related parameters, could be connected with

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QoS (*Quality of Service*). In [5], QoS definition is given as: ''Totality of characteristics of a telecommunication service that bear on its ability to satisfy stated and implied needs of the user of the service''. Stankiewicz *et al.* [10] give a broader explanation of QoS and for that purpose, they define three levels of QoS: based, perceived and evaluated. Regardless of differences in QoS and QoE definitions, in terms of QoS/QoE ECOSYSTEM, the authors apostrophize in separate papers [11], [12] that QoE can be associated with QoS performance, or in other words, the aspects of system performance have a significant impact on the final dimension of QoE. In order to estimate a relationship between QoS and QoE, authors have mainly dealt with correlations between sets of AQoS (*Application QoS*) or NQoS (*Network QoS*) parameters and QoE, thereby paying less attention to contribution of low layers in this paradigm [13], [14]. Various QoS mechanisms [15], which are based on the classes [16], provide adequate QoS in core and aggregation networks and consequently acceptable systematic factors for good QoE. On the other side, access network, which connects customers over different transmission media with operator's first telecommunication node, can introduce a new form of QoS issues. For example, parameters such as noise level, number of FEC (*Forward Error Corrections*) indications, number of ARQs (*Automatic Repeat Requests*), frame losses, maximum channel capacity, PSD, attenuation and interleaving depth describe situation in the transmission channel. They can be used as CQIs (*Channel Quality Indicators*) that relate to PHY (*Physical*) and MAC (*Media Access*) layer in DSL (*Digital Subscriber Line*) network. A sudden appearance of additional noise or changes in transfer function of the communication channel will cause packet losses and additional packet delays which leads to negative QoS changes. During these appearances, some of CQIs will change their values and indicate the change in the transmission channel.

Hence, in this paper, we proposed a practical mathematical model that uses statistical analysis of CQIs, that we called QoPH (*Quality of Physical channel*) parameters, in order to estimate values of QoS indicators. The model assumes that telecommunication systems are designed to cope successfully with Gaussian noise and that it is necessary to consider only appearance of additional stationary or non-stationary noise in the communication channel, which highly affects QoS indicator disorders. These appearances, as well as CQIs that indicate them, can have different probability distribution. Contrary to finding likelihood function, the model performs time series analysis of each CQIs to find their autocorrelations and cross-correlations. For this purpose, it used combination of SSA (*Singular Spectrum Analysis*) and DPCA (*Dynamic Principal Component Analysis*) mathematical analysis by using Hotelling's T-squared distribution in order to form the needed number of vectors in new QoPH space. These vectors discover time intervals with the largest change of QoS indicator values and transform QoPH into QoS space. The model enables estimation of relationship between QoS and QoE by using analytical (IQX hypothesis [17]) or objective methods (such as SSIM) in post video analysis. In this way, the model considers contribution of access network in overall QoS/QoE paradigm at customer side without additional measurements of various QoS indicators. Many of existing telecommunication systems are equipped with hardware and software which enables them to conduct different network tests in certain time intervals. During these tests, a system can collect values of CQIs from PHY and MAC layer, which we can use as input in the model. One typical example of the system is DSLAM (*Digital Subscriber Line Access Multiplexer*), which is equipped with SELT (*Single End Line Test*) or DELT (*Dual End Line Test*) possibilities that can generate a huge set of CQIs. Obtaining CQIs can also be accomplished by installing active measuring system in specific points at telecommunication network. The model has no limit in terms of the number of variables that can be used as inputs because it finds all possible correlations which are supposed to cause changes of QoS indicators. In this way, the proposed mathematical model expends QoS/QoE paradigm onto low layers of OSI (*Open System Interconnection*) reference model. Verification of the model was conducted by an experimental method in the network of telecommunication service provider BH Telecom JSC Sarajevo. The method included the use of the IPTV system.

II. RELATED WORKS AND MOTIVATIONS

Network operators and service providers often face the problem of fulfilling SLA (*Service Level Agreement*) at some unspecified user groups that occasionally have a disturbance at video service noticed as video degradations. This situation is very common in the last mile of the telecommunication network and apparently, in these cases, users are facing a problem of QoS fulfillment and consequently with low level QoE. This problem, which is related to the issues in transmission channel, cannot be noticed by elements of telecommunication network except by measurements or by system monitoring. Even then, there is no method to estimate how long the problem lasted and how it affected QoS and QoE. The most papers deal with QoS/QoE correlations in which authors consider analytical and objective methods that include relationship between QoE and parameters of higher OSI layers such as packet loss, delay, jitter, frame loss, MDI (*Media Delivery Index*), throughput or bandwidth [18], [19]. In addition to this, a number of papers have investigated cases of how protocols like TCP (*Transport Control Protocol*) or UDP (*User Datagram Protocol*) and QoS control mechanisms affect QoE [20], [21]. Authors also dealt with how GOP (*Group of Picture*) i.e. order of I, P, B frames affects QoE [22]. On the other hand, QoE is a much broader concept and includes different aspects of communications and service acceptance. However, Fiedler *et al.* [17] have tried to find analytical solution of QoS/QoE correlation considering differential equation $\frac{\partial QoE}{\partial QoS} = -\beta \cdot (QoE - \gamma)$. This attempt generated one no-reference techno-centric view of QoE which takes into account QoS indicators of higher OSI layers. Contrary to previous equation, we tried to find a solution to another more complex differential equation $\frac{\partial QoE}{\partial QoPH} = \frac{\partial QoE}{\partial QoS} \cdot \frac{\partial QoS}{\partial QoPH}$ by statistical analysis. Therefore, motivation for building the mathematical model, described in the paper, was the lack of the one that maps the quality of transmission channel into QoS and after that into QoE space without analyzing the system function but only physical parameters. In order to consider correlations between physical layer parameters, QoS and QoE, authors in [23]–[25] offered cross-layer design solutions, which take into account the estimation of line rate, signal power, coding as well as their adaptation to application requirements in the specific network conditions. However, they have considered parameters passively without involving mutual correlations. Appearance of additional sudden noise that affects QoS changes was not included into the design. Rivas *et al.* [26] are trying to find correlation between the physical layer of LTE radio configuration and QoS parameters of application layer in order to optimize the relation between QoS and QoE. They noticed that impact of the physical layer on QoE is evident but they did not present a mathematical model. Zheng *et al.* [27], [28] also deal with the domain of the influence of wireless network configuration on QoE over QoS parameters. They concluded that it is a challenge to provide QoS in wireless environment due to dynamics of the wireless channel. Chen *et al.* [29] proposed near optimal power allocation scheme for transmitting SVC (S*calable Video Coding*) based videos over MIMO (*Multi-Input Multi-Output*) system that are targeting at maximizing QoE. This kind of optimization scheme that combines pieces of PHY and APP level information would welcome the proposed model in this paper since it allows detection of changes in PHY and MAC parameters and helps in finding intervals when that optimization is needed. Concerning fixed access network, in TRs (*Technical Reports) [30], [31]*, which deal with DSL issues, group of authors formulated a certain set of requirements for proper IPTV service recommended in the form of technological improvements based on DSM (*Dynamic Spectrum Management*), vectoring, enhanced impulse noise protection, SRA, AL-FEC (*Application Layer - FEC*) and measurements. Andersson *et al.* [32] studied influence of impulse noise and seconds with block errors onto QoS parameters. In [33], they also studied physical layer disturbances and network layer packet loss relation in an OFDM (*Orthogonal Frequency Division Multiplex*) based system. Although, in ITU recommendation [34], E2E (*End-to-End*) QoE applies to an end user, a very small number of authors, except [35] and [36], deal with sphere of home and access networks. These authors emphasize it is necessary to observe every technological segment that contributes to estimation of QoE for completing the requirements given in ITU recommendations. They concluded that modelling of these segments, i.e. segments of access and home network, is immensely significant to ensure E2E QoS as well as E2E QoE. For this purpose authors have introduced, in [37], mPlane, a system for E2E unveiling network and service degradations. They noticed that service degradations are very rare with QoS mechanisms embedded in core networks and their occurrence is usually linked to the last mile. Because of that, it is very important to emphasize that problems, generated in the transmission channel, are very serious, stochastic and their impact on the performance of QoS, as well as perceived quality by users, is necessary to be investigated. An interesting study was explained in [38]. In this study, the authors proposed, in order to achieve a certain level of QoE, the network needs to adapt multimedia service by influencing the amount of bit delivery especially in the case of degradation of multimedia service during appearance of continuous errors. They tested performance of FEC mechanisms in order to find optimal FEC design for achieving higher level of QoE of VoIP services. MOS, defined over PESQ score that compares degraded and original audio clip, is used as an indicator of user quality perception. In order to find some relations between QoS parameters and QoE other authors have researched modelling of structural equations and got the results in local form [39]–[41]. Statistical analysis used in these papers is often based on ML (*Maximum Likelihood*) estimation and mostly regression analysis of the known values. The concept of bottom-to-up approach from physical layer to layer of perceived QoE was made in [42]. They concluded that very few papers deal with QoS/QoE problem based on lower layers.

III. AN EXAMPLE OF CQIs IN FIXED ACCESS NETWORK

Many PHY and MAC parameters monitored on a system can be used for measuring the quality of transmission channel. These parameters show the state in the channel and their choice depends on the service and the system used to deliver the service. In the OFDM case, every channel has maximum capacity rate R_c which can be presented by [43]:

$$R_c = \frac{1}{N}\sum_n \log_2\left(1 + \frac{SNR_n}{G + nm}\right) \tag{1}$$

In (1) $SNR_n = \frac{H_n P_n}{N_i}$ denotes ratio between channel gain H_n, power on *n-th* subcarrier P_n, and sum of Gaussian noises N_i. In the denominator of (1), G denotes "gap" and *nm* denotes noise margin that is specified to provide additional certainty in the system. Noise margin for maximum capacity rate R_c is approximately 6 to 10 dBs and depends on a service. If a service has rate R_s, it must satisfy the next condition:

$$R_s < R_c \leq C_{awgn} \tag{2}$$

For proper service delivery, it is obvious that service rate R_s must not exceed maximum capacity rate R_c which must not exceed capacity of AWGN (*Additive White Gaussian Noise*) channel C_{awgn}. The stability of parameters from (1) is the second condition that needs to be satisfied during service delivery. Service rate R_s has similar form as (1) with a different noise margin value. In this case, noise margin needs to be higher than 6-10 dBs for a particular service rate. If service rate fulfills (2) and parameters from (1) are stable, we assume that service is "*in control*". In that case, it can be assumed that there are only Gaussian sources in transmission channel. If noise increases, parameters from (1) which are causing bit errors change. Error control system will react and try to fix appearance of bit errors, which as result gives the increase of FEC incidents and ARQ requests. If noise is non-stationary and long lasting, system will not be able to correct all errors, thus frame losses will appear as well as consequent packet losses and additional delays. In this case, IPTV service that uses MPEG TS for transport of video packets and which is multiplexed in UDP will be irretrievably exposed to packet losses. These protocols for video packet transmission are not connection-oriented and every packet loss leads to distortion of QoS indicators, which consequently leads to lower level of QoE. In that moment, the values and relations between monitored PHY and MAC layer parameters give a good base for considering influence of access network on QoS/QoE relation.

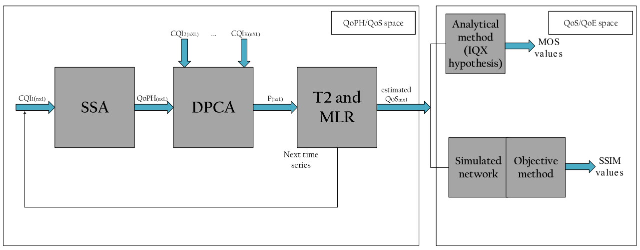

FIGURE 1. **The model design.**

IV. THE MODEL DESIGN

Proposed mathematical model, depicted in Fig. 1, consists of blocks that serve to estimate values of QoS indicators in near real time. It uses discrete values of CQIs, collected on physical and data link layer, which indicate quality of communication channel and its stability. The model recognizes two states: "*in control*" in which there are only Gaussian noise and "*out of control*" in which there is appearance of additional transmission problems. In the SSA block, the model monitors a CQI time series, discovers its dynamics and finds changes in the time series. By comparing the original series with ergodic ones, it also discovers the exact number of autocorrelation coefficients and duration of time changes (L-order). After SSA block, the time series with other CQIs creates Hankel matrix and enters DPCA block. In this block, the original matrix space transforms into its eigenvalues and eigenvectors. The result is new P vectors, which are oriented to maximum variance of CQI matrix space. In the next block, by using Hotelling's T^2 statistics [44], the model selects vectors that exceed ellipsoid given by F distribution. This ellipsoid defines boundaries between two states. Vectors that fall into the boundaries are the consequence of existing noise sources. Contrary to this, vectors that fall out of them are the consequence of additional transmission problems. These exceeded values are subject to additional MLR (*Multiple Linear Regression*) analysis in this block. In this part, the model, by comparing QoS vectors of similar service delivery cases, finds coefficients that enable estimation of the next value of any QoS indicator. In the QoS/QoE space, QoE can be checked by analytical or objective methods. Analytical method uses estimated QoS values in order to find IQX hypothesis while objective method uses them in simulated network. After the simulation, objective method allows QoE estimation without user involvement with the use of frame-by-frame analysis.

V. FUNCTIONING OF THE SSA BLOCK

SSA analysis of time series, mentioned in [45], is used in many research areas like chemistry [46], economy [47], and meteorology [48]. SSA block in the model is designed to monitor one of CQIs of communication channel in order to discover appearance of transmission problem. The selected parameter has values which are observed and collected in equal time interval. A series of these values represents one realization of random process i.e. random time series. In [49], authors considered parameters such as noise margin, SNR and maximum attainable rate, which indicate quality of the channel and can be used for QoS estimation. In the same paper, authors concluded that frame loss happened during noise margin instability, which led to IP packet losses and consequently video degradations. They described this occurrence by ARIMA (Autoregressive Integrated Moving Average) model and concluded that changes of noise margin were contained in its autocorrelation function. For this reason, the noise margin was chosen in the proposed model to be monitored in SSA block. We used a set of equations represented in [50] in order to describe SSA functionality. In this paper authors analysed vector signal transmission through a channel. On the received side, signal **s** in AWGN channel, with noise vector **W** that consists of independent identically distributed (i.i.d.) standard Gaussian variables and linear channel transfer matrix **H**, can be represented as:

$$\mathbf{x_s} = \mathbf{H} \cdot \mathbf{s} + \mathbf{w} \tag{3}$$

If we observe n samples of received vector $\mathbf{x_s(n)}$ of received signal $\mathbf{x}$ that are normally distributed and independent of $\mathbf{W}$ noise vector, according to [51], the two hypothesis can be tested:

$$\mathbf{x_s(n)} = \begin{cases} \mathbf{w_i(n)} & \mathcal{H}_0 \\ \mathbf{H(n)} \cdot \mathbf{s(n)} + \mathbf{w_i(n)} & \mathcal{H}_1 \end{cases} \tag{4}$$

In (4), $\mathbf{x_s(n)}$ represents subseries which consists of n samples, $\mathbf{w_i(n)}$ represents vector samples of independent Gaussian variables, $\mathbf{s(n)}$ and $\mathbf{H(n)}$ represent signal and transfer channel matrix respectively. Considering (4), we can conclude, if the null hypothesis is true there aren't any signals in random series i.e. $\mathbf{x_s(n)} = \mathbf{w_i(n)}$. On the contrary, if there are signals in snapchat vectors $\mathbf{x_s(n)}$, the second hypothesis is valid. Considering (3), as well as equations which are explained in [50], covariance matrix of signal group in AWGN channel can be represented as a relation between signal decomposition, its channel transfer function and

AWGN:

$$\mathbf{X_s} = \frac{1}{p}\sum_{s=1}^{p} \mathbf{x_s x_s^T} = \mathbf{HSH^H} + \boldsymbol{\sigma}^2\mathbf{I} = \mathbf{U_s \Lambda_s U_s^T} \quad (5)$$

Matrix $\mathbf{\Lambda_s}$ from (5) is diagonal matrix which consists of k eigenvalues λ_i, which define number of active signals, sorted by decreasing order and such that $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \ldots \lambda_k$ and that least p-k values equal variance of AWGN noise, or:

$$\lambda_{k+1} = \lambda_{k+2} = \ldots = \lambda_p = \sigma_n^2 \quad (6)$$

Considering preceding statements, it is obvious that p-k eigenvalues of AWGN noise can be separated from k values, which define base signals. Using (4) and (5), hypotheses can be transformed into the following:

$$\mathbf{X_s} = \begin{cases} \sigma^2\mathbf{I} & \mathcal{H}_0 \\ \mathbf{HSH^H} + \sigma^2\mathbf{I} & \mathcal{H}_1 \end{cases} \quad (7)$$

Now, if transfer matrix H and signal matrix S are constant, the change of X_s in the hypothesis one can occur only in the case of noise rising. Mathematically, this increase, also (i.i.d), leads to the next equation:

$$\mathbf{X_s} = \mathbf{HSH^H} + (\sigma^2 + \sigma_\Delta^2)\mathbf{I} \quad (8)$$

Using (4-8), it can be concluded that hypothesis system will be changed after the appearance of additional noise σ_Δ^2 and then there will be k eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \ldots \lambda_k$ which define signals and least m-k eigenvalues that equal variance of noise $(\sigma^2 + \sigma_\Delta^2)$. The second part of (8) that is generated by additional noise will last until noise exists. During noise appearance, according to previous observations, initial hypothesis will take another form:

$$\mathbf{X_s} = \begin{cases} \mathbf{HSH^H} + \sigma^2\mathbf{I} & \mathcal{H}_0 \\ \mathbf{HSH^H} + (\sigma^2 + \sigma_\Delta^2)\mathbf{I} & \mathcal{H}_1 \end{cases} \quad (9)$$

Considering the previous analysis and comparing equations (5) and (9), matrix $\mathbf{\Lambda_s}$ can be used to discover appearance of additional noise. Now, if we define new covariance matrix $\mathbf{X_H}$ of Hankel matrix, where $\mathbf{x_i}$ are lagged CQI vectors in Hankel matrix, we can make decomposition of that matrix in its eigenvectors contained in $\mathbf{U_H}$ matrix and eigenvalues λ_H contained in matrix $\mathbf{\Lambda_H}$:

$$\mathbf{X_H} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{m} \mathbf{x_i x_j^T} = \mathbf{U_H \Lambda_H U_H^T} \quad (10)$$

In (10), *n* and *m* denote number of rows and columns of Hankel matrix. Eigenvalues λ_{Hi} show direction of the biggest variance of $\mathbf{x_i}$ vectors. In the model, vectors $\mathbf{x_i}$ represent *m* lagged time series of a selected CQI and therefore the biggest eigenvalues λ_{Hi} represent a number of autocorrelation coefficients needed for discovery of CQI dynamics. In accordance with [52] and [53], the decision threshold T_{NP} can be defined as Neyman–Pearson relation for hypothesis testing:

$$T_{NP} = \frac{\max_{\sigma_\Delta \cdot \sigma_n} L(\sigma_\Delta, \sigma_n; x_1, x_2, \ldots, x_k)}{\max_{\sigma_n} L(\sigma_n; x_1, x_2, \ldots, x_k)} \quad (11)$$

In numerator of (11), there is a maximum likelihood function of variences of additional and Gaussian noise, and in denomenator maximum likelihood function of Gaussian noise. If T_{NP} is greater than defined threshold *t*, it is decided in favor of H_1, and in contrary, in favor of H_0. Using the analysis from equalities (7-9), we can form Hankel matrix $\mathbf{X_H}$ of CQI and Hankel matrix $\mathbf{X_{H\_awgn}}$ created by AWGN noise. Presence of only AWGN noise in the channel can be assumed as "*in control*" condition i.e. a condition in which the main signal is weakened by only AWGN noise. On the contrary, "*out of control*" condition can be defined as appearance of additional transmission problems defined in the second part of (9) withH_1 hypothesis. When $\mathbf{X_H}$ and $\mathbf{X_{H\_awgn}}$ matrices are compared, hypothesis test from (11) can be transformed in the next form, where threshold $t = \sigma_n^2$:

$$\begin{cases} \dfrac{\sqrt{\sum_{n=1}^{L} \lambda_{h_n}^2}}{\sqrt{\sum_{i=1}^{L} \lambda_{h\_awgn_i}^2}} \leq \sigma_n^2 & \mathcal{H}_0 \\ \dfrac{\sqrt{\sum_{n=1}^{L} \lambda_{h_n}^2}}{\sqrt{\sum_{i=1}^{L} \lambda_{h\_awgn_i}^2}} > \sigma_n^2 & \mathcal{H}_1 \end{cases} \quad (12)$$

Now, the relation of the sum of Frobenious norms of eigenvalues from matrix $\mathbf{\Lambda_H}$ and eigenvalues of test AWGN matrix $\mathbf{\Lambda_{H\_awgn}}$ has to be tested. Considering (12), if there is no other noise source besides AWGN noise, characteristic matrices have the same Frobenious norms and they satisfy hypothesis $\mathcal{H}_0$. On the other side, if there are other noise sources in observed time series, Frobenious norms will not be equal and hypothesis H_1 will be satisfied. Since there are many time intervals, the model divides time series of observed CQI into a number of smaller subseries to facilitate the test. After the division, the whole series $x_S = \sum_{i=1}^{n} x_{si}$ represents the sum of smaller subseries. Considering SSA analysis, it is possible to make Hankel's matrix of each subseries. Each covariance of Hankel's matrix can be transformed into own eigenvectors which are contained in matrix $\mathbf{U_{Hsi}}$ and own eigenvalues which are contained in matrix $\mathbf{\Lambda_{Hsi}}$. For each of them the model tested the hypotheses from (12) in order to find a change point where additional noise appeared. When $\mathcal{H}_0$ is satisfied, creating of Hankel's matrix can be continued by adding new lagged vectors and after that testing hypothesis can be applied again. It is obvious that addition will be continued until $\mathcal{H}_1$ is achieved. That is the moment of noise transition. Division of time series into less intervals can relieve a larger number of transitions. After discovering noise transition, the model needs to find the correlation order L. For this purpose the model uses next equation:

$$\frac{\sum_{i=1}^{L+1} \lambda_i}{\sum_{i=1}^{L} \lambda_i} \cong 1 \quad (13)$$

The next lagged vector subseries x_{si} will be added as long as the condition, from (13), is not reached. However, due to the nature of signal transmission through the communication channel i.e. its nonlinear effects, and due to the presence of

AWGN noise, identification of number of lagged vectors by using (13) is not always clear. Small fluctuations of eigenvalues are always present, especially when their values approach normalized variance of AWGN noise ($\sigma_n^2 = 1$). This leads to very hard decisions of how many vectors need to be added to define the size of correlation order L. Therefore, besides criterion from (13), the next criterion should be considered:

$$\lambda_i - \text{mean}\left(\Lambda_{Lxm}\right) > 0 \quad i = 1, \ldots, m \tag{14}$$

This criterion defines i-th eigenvalue, when the next one does not influence the number of correlations L and vectors needed for reconstruction time series treated by SSA analysis. These two criteria, (13) and (14), should merge to achieve the precise number of correlation order L. By normalizing (13) for each sum of relations between eigenvalues λ_i, vector $\mathbf{v_r}$ can be formed as follows:

$$\mathbf{v_r} = \frac{\frac{\sum_{i=1}^{L+1}\lambda_i}{\sum_{i=1}^{L}\lambda_i} - \min\left(\frac{\sum_{i=1}^{m}\lambda_i}{\sum_{i=1}^{m-1}\lambda_i}\right)}{\max\left(\frac{\sum_{i=1}^{m}\lambda_i}{\sum_{i=1}^{m-1}\lambda_i}\right) - \min\left(\frac{\sum_{i=1}^{m}\lambda_i}{\sum_{i=1}^{m-1}\lambda_i}\right)} \tag{15}$$

Also by considering (14), for each eigenvalue λ_i, the vector $\mathbf{v_{sv}}$ can be formed:

$$\mathbf{v_{sv}} = \frac{\left(\lambda_i - \text{mean}\left(\Lambda_{Lxm}\right)\right) - \min\left(\lambda_i\right)}{\max\left(\lambda_i\right) - \min\left(\lambda_i\right)} \quad \text{where } i = 1, \ldots m \tag{16}$$

After this, the model combines next equations for each vector element to get new criterion:

$$L = \text{Min}(\mathbf{k}) = \sqrt{|\mathbf{v_{ri}}|^2 + |\mathbf{v_{svi}}|^2)} \quad \text{where } i = 1, \ldots, m \tag{17}$$

The smallest of the elements of the vector $\vec{k}$, formed by roots of the vectors squares from (15) and (16), is used for defining the needed number of eigenvalues or correlation coefficients to determine L-order used in Hankel's matrix.

PSEUDO CODE

1. The model considers N discrete observations of one CQI in time τ;
2. N discrete observations represent the base sequence in form of $X = H * X_s + N$;
3. This matrix transforms in Hankel matrix with arbitrary number of offsets L;
4. Finds covariance of Hankel matrix $C = X_H * X_H^T$;
5. Performs SVD (*Singular Value Decomposition*); Result is U_s and Λ_s matrices;
6. Calculates Frobenious norm or Euclid distance of Λ_s; Creates test matrix X_{HAWGN};
7. Performs SVD; Result is U_{AWGN} and Λ_{AWGN} matrices;
8. Calculates equation (12); Checks hypothesis $\mathcal{H}_0$ or $\mathcal{H}_1$;
9. If $\mathcal{H}_0$ is satisfied, go to 1.
10. If $\mathcal{H}_1$ is satisfied, go to DPCA block and check criterion from equations (13-17)

VI. DPCA, DECISION AND MLR BLOCK

After SSA block, the model adds the rest of CQIs parameters with L-order of correlations to the next block. CQIs of data link layer, such as number of FEC incidents and/or number of ARQs, represent a response of error control system to appearance of bit errors into physical layer. These indicators show how interference or disturbance in transmission channel affect channel quality. If quality of the channel changes, values of CQI will have a negative or positive linear trend. Hence, it is necessary to form a new block that, besides autocorrelation discovered in SSA block, discovers cross correlations between CQIs. In DPCA block, Hankel matrix with lagged sequences is formed in order to perform PCA (Principal Component Analysis) [54]. According to [55] and [56], a Hankel matrix from DPCA block can be mathematically represented by the next equation:

$$\mathbf{QoPH_{nx(K\cdot L)}} = \begin{vmatrix} X_1^I & \cdots & X_L^I \\ \vdots & \ddots & \vdots \\ X_n^I & \cdots & X_{n-L}^I \end{vmatrix} \begin{vmatrix} X_1^{II} & \cdots & X_L^{II} \\ \vdots & \ddots & \vdots \\ X_n^{II} & \cdots & X_{n-L}^{II} \end{vmatrix} \cdots \begin{vmatrix} X_1^K & \cdots & X_L^K \\ \vdots & \ddots & \vdots \\ X_N^K & \cdots & X_{n-L}^K \end{vmatrix} \tag{18}$$

Matrix QoPH from (18) represents vector space, which is formed from K normalized variables i.e. values of CQIs. From each of them, mini-matrices of *L* lags and *n* observations taken in *n* discrete regular measuring intervals are created. Covariance matrix **C**, dimensions $(K \cdot L)x(K \cdot L)$, for matrix space from (18) can be found by:

$$\mathbf{C} = \frac{1}{n}\left[\mathbf{QoPH_{nx(K\cdot L)}}\right]^T\left[\mathbf{QoPH_{nx(K\cdot L)}}\right] \tag{19}$$

It is obvious that matrix C from (19) is symmetrical and positively definite and we can find its eigenvectors and eigenvalues. That can be shown as:

$$\mathbf{C} = \mathbf{A} \cdot \mathbf{\Lambda_{K\cdot LxK\cdot L}} \cdot \mathbf{A^T} \tag{20}$$

In (20), $\mathbf{\Lambda}$ denotes diagonal matrix dimensions $(K \cdot L)x(K \cdot L)$, in which $K \cdot L$ denotes non-null eigenvalues of matrix **C** i.e. $\mathbf{\Lambda} = \text{diag}(\lambda_1, \lambda_2, \lambda_3, \ldots)$, which are arranged by descending order. In addition, eigenvalues have to satisfy the following $\lambda_1 > \lambda_2 > \lambda_3 > \ldots\lambda_{K\cdot L} > 0$. Matrix of eigenvectors **A** has dimensions $nx(K \cdot L)$ and it consists of (n-L) orthonormal eigenvectors such as $\mathbf{A^TA} = \mathbf{I_{n-L}}$ is valid. In literature, matrix **A** was called *loading* matrix. PCA, which is performed over the vectors from (18), as a result, gives new less dimensional vector space. The new vector space consists of eigenvalues and eigenvectors arranged in descending order according to the size of the variance and covariance of basic **QoPH** vectors. Combining matrices **QoPH** and **A** can be presented mathematically as:

$$\mathbf{P} = \mathbf{QoPH} \cdot \mathbf{A} \tag{21}$$

In accordance with Hotelling's T^2 statistics from [41], the following equation can be written as:

$$T_k^2 = (\bar{x} - \mu)^T \left(\mathbf{QoPH^T} \cdot \mathbf{QoPH}\right)^{-1} (\bar{x} - \mu) \quad (22)$$

In (20) $\bar{\boldsymbol{x}}$ and $\boldsymbol{\mu}$ denote vectors of expected and average values, while **QoPH** represents matrix of lagged CQIs. Using the combination of (18) and (20), the equation (22) can be presented as:

$$T_k^2 = (\bar{x} - \mu)^T \left(\mathbf{A \Lambda A^T}\right)^{-1} (\bar{x} - \mu) \quad (23)$$

For each p-dimensional vector from (19), after other PCA transformations and normalizations, Hotelling's T^2 statistics is converted in the form:

$$T_k^2 = (\mathbf{pA})^T \left(\mathbf{A \Lambda A^T}\right)^{-1} (\mathbf{pA}) \quad (24)$$

After some calculations, we get:

$$T_k^2 = \mathbf{p^T} (\mathbf{\Lambda})^{-1} \mathbf{p} \quad (25)$$

We assume that (25) has F-distribution:

$$\mathbf{p^T} (\mathbf{\Lambda})^{-\mathbf{1}} \mathbf{p} => \frac{k\,(n-1)}{n-k} \mathcal{F}_{k,n-k}(p) \quad (26)$$

and if changes of QoPH space are in accordance with AWGN this statistics does not exceed defined α-value. For identifying changes, Hotelling's T^2 statistics needs to be checked for each eigenvector in new QoPH vector space, so that the value greater than the value obtained by Fisher's distribution is included into the further consideration. Each vector, which satisfies requirements of F-distribution, represents points which lie within n-dimensional ellipsoid. Vectors which fall into n-dimensional ellipsoid are considered as a consequence of AWGN. So, vectors which fall outside n-dimensional ellipsoid are considered as outliers i.e. **p** vectors that contribute the most to deviation values of QoS indicators. The model choses only the greatest vectors from **P** (also L-order) and forms Hotelling's T^2 statistics, which is represented by the next equation:

$$T_i^2 = \sum_{i=1}^{L} \left(\frac{\mathbf{p_i}}{\lambda_i}\right)^2 > \frac{k\,(n-1)}{n-k} \mathcal{F}_{k,n-k}(p) \quad (27)$$

In (27), $\mathbf{p_i}$ denotes rotated value of eigenvector of i-th row while λ_i denotes eigenvalue of i-th row λ_i which is a standard deviation of grouped CQI. Vectors for which T_i^2 is greater than the value of F-distribution represent deviations that should be correlated with values of QoS indicators. Authors noticed in [57] and [58] that a number of packet loss increases along with dispersion of CQI. We also assume that changes in communication channel can be detected by SSA while DPCA and T^2 statistics discover effects of these changes. Using time values of QoS indicators, **QoS** matrix $\mathbf{QoS_{kxN}} = \left[\mathbf{QoS_1}, \mathbf{QoS_2}, \ldots, \mathbf{QoS_N}\right]$ can be formed as to consist of $\mathbf{QoS_i}$ vectors $\mathbf{QoS_i} = \left[qos_1, qos_2, \ldots qos_k\right]^T$, where qos_i represents an element of particular $\mathbf{QoS_i}$ vector. Since every $\mathbf{QoS_i}$ vector depends on $\mathbf{p_i}$, in case of linear dependency, we can form the next equation for each vector:

$$\mathbf{QoS_i} = \mathbf{b_0} + \mathbf{b_i p_i} \quad (28)$$

The (28) represents a form of MLR (*Multivariate Linear Regression*) analysis between adopted new QoPH vector space and values of QoS indicators. If PCA components of QoPH vector space are selected in such a manner as presented in inequality (27), then the components, with the lowest standard deviation (the smallest diagonal members matrix eigenvalues Λ), will be eliminated. The reason is very little or no impact on the correlation with the vector $\mathbf{QoS_i}$. These components, associated with AWGN noise, have a multi-dimensional normal distribution and are considered not to affect leading the system in the state "*out of control*." Only components that fall outside the n-dimensional Fisher's ellipsoid contribute to this state. For this reason, in the case of Hotelling's T^2 statistical analysis, the model only considers vectors with large deviations because they explain best the mutual correlation time series of CQIs and QoS indicators. Coefficients $\mathbf{b_i}$, from (28), can be estimated by the least squared method of previous measured QoPH and QoS sequences that can be presented by:

$$\mathbf{b_i} = \left(\mathbf{p_i^T p_i}\right)^{-\mathbf{1}} \mathbf{p_i^T} \widehat{QoS}_\mathbf{i} \quad (29)$$

MLR block allows estimation of the next value of any QoS indicator, after calculating the coefficients b_i, which are a result of (29).

PSEUDO CODE – CONT.

1. Creates Hankel's matrix using (18) in accordance with L-order obtained from SSA;
2. PCA is applied on covariance of Hankel's matrix;
3. T^2 is found for each vector from matrix C;
4. In accordance with (27) vector selection is made for L-order; vectors which fall into ellipsoid formed by F-distribution are the result of Gaussian noise (*NO ALARM* state), while vectors which fall out of ellipsoid boundaries are the consequence of additional noise (*ALARM* state);
5. MLR is performed between selected vectors and previous QoS indicator's values; *b* coefficients were given;
6. Using (28) the model performs estimation of QoS indicator's values;

VII. QoE ESTIMATION IN THE MODEL

The model can be expanded into QoE space by using objective or analytical methods. Although analytical and objective methods for QoE testing, due to different factors, make an inaccuracy in relation to the subjective, many of researchers use them to evaluate QoE. The authors in [17] took the following differential equation as the starting point for analytical approach:

$$\frac{\partial QoE}{\partial QoS} = -\beta \cdot (QoE - \gamma) \quad (30)$$

In (30), β and γ represent coefficients that were found by regression analysis. Solution to this equation, in the case of packet loss, was represented by the following equation:

$$QoE = 3,01e^{-4,473 \cdot PL} + 1,065 \quad (31)$$

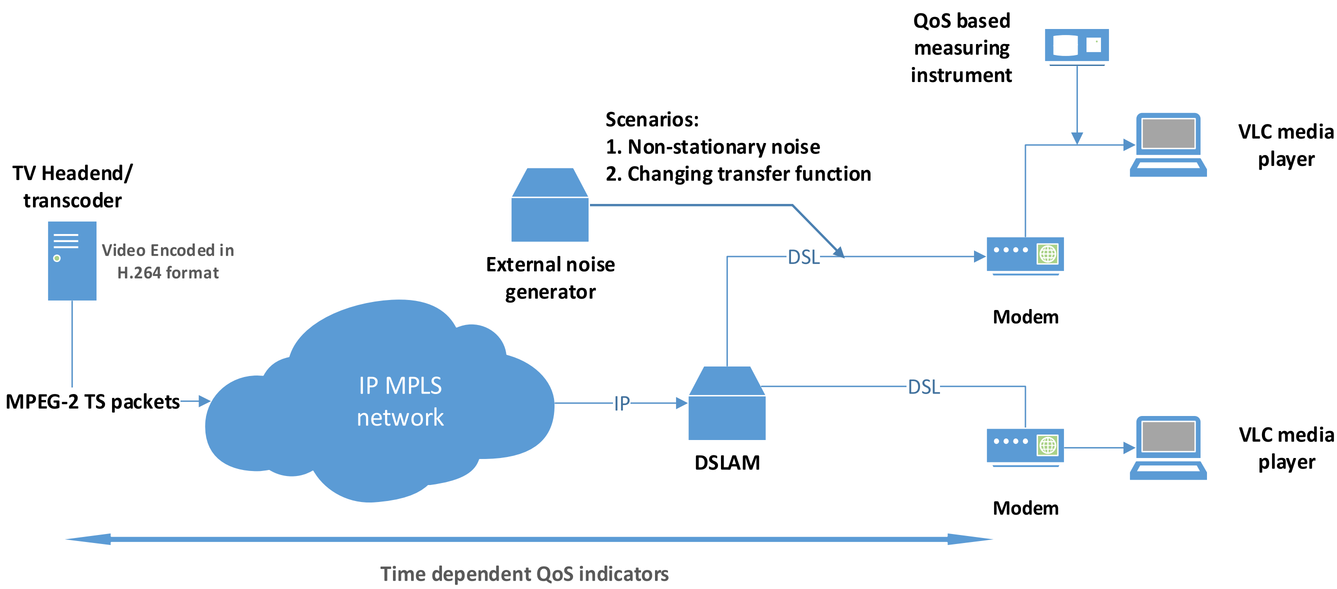

FIGURE 2. Test scenarios.

For analytical approach, the model uses simple IQX hypothesis from (31), taken in different time intervals, which shows values of QoE using the following:

$$\mathrm{QoE_i} = \left[\gamma \mathrm{e}^{-\beta \mathrm{qos}_1}, \gamma \mathrm{e}^{-\beta \mathrm{qos}_2}, \ldots, \gamma \mathrm{e}^{-\beta \mathrm{qos}_k}\right]^{\mathrm{T}} \tag{32}$$

In (32), $\mathrm{QoE_i}$ presents QoE values, which are calculated for each element of any $\mathbf{QoS_i}$ vector by regression analysis. If other QoS indicators are considered, unique time-dependent scalar of QoE value can be calculated by averaging the obtained values of each member of the $\mathrm{QoE_i}$ set. It is obvious that (32) represents time expansion of basic IQX hypothesis on parameter basis. Estimated $\mathbf{QoS_i}$ values from (28), beside depicted analytical method, can be used for objective QoE testing. Objective method is used after conducting a simulation in NS2 simulator that was extended with EvalVid. We created a network in the simulator as we did in experimental case and tuned conditions in the simulated network in order to get QoS indicator values from (28). The original video in H.264 format was transferred through the simulated network and captured at its end in a separate file with .mp4 extension. The original and resulting videos were compared by SSIM method.

VIII. EXPERIMENTAL VERIFICATION OF THE MODEL

Verification of the proposed mathematical model was tested by considering IPTV service delivered over telecommunication network of one local network operator in Bosnia and Herzegovina (BH Telecom JSC Sarajevo). IPTV service was delivered from TV Headend to tested DSL lines over QoS guaranteed core and aggregation network in which various QoS mechanisms are implemented. Practically, this means that core and aggregation segments of network have no effect on changes in the value of QoS indicators. The changes of indicator values are caused only by external factors generated in the access network. At this point, we have introduced additional noise by external device in order to cause the change of SNR in a DSL line as well as capacity of transmission channel. There are two most frequent cases of disturbances on DSL line that are related to sudden rising of noise and changing of primary parameters R, L, C or G of DSL lines. For this reason, we have chosen to perform experiments, which include these two cases. Hence, verification of the model is performed by experiment in accordance with two scenarios depicted in Fig. 2. First of them is related to the case of video analysis during introduction of non-stationary impulse noise on DSL line and the second one is related to the case of video analysis during appearance of intermittent connection which was accomplished by changing line parameters. In both scenarios, two identical IPTV video streams with sport content (res. 720 × 576, 25 fps) are encoded in H.264 format and distributed from TV Headend over provider's network to users. At the beginning of transmission, original video was converted in MPEG-TS video packets that had been captured on two completely separate DSL lines on the site of IPTV user. Video was distributed over IP/MPLS network with high-level QoS in core and aggregation network i.e. without loss, very low delay and tolerant jitter (<2,2ms) and reproduced on VLC clients. During experiments, a video from degraded and non-degraded lines was captured in order to get SSIM values for QoE evaluation. SSIM values are compared by using VQMT (*Video Quality Measurement Tool*). Video synchronization is achieved in offline video analysis using FFmpeg tool i.e. setting any of selected frames as a reference frame for both videos. QoS-based measuring system, used in both scenarios, was able to measure the current value of QoS, which had been used for comparison with estimated QoS values obtained by the mathematical model. In particular time intervals, one of DSL lines was exposed to systematic interference

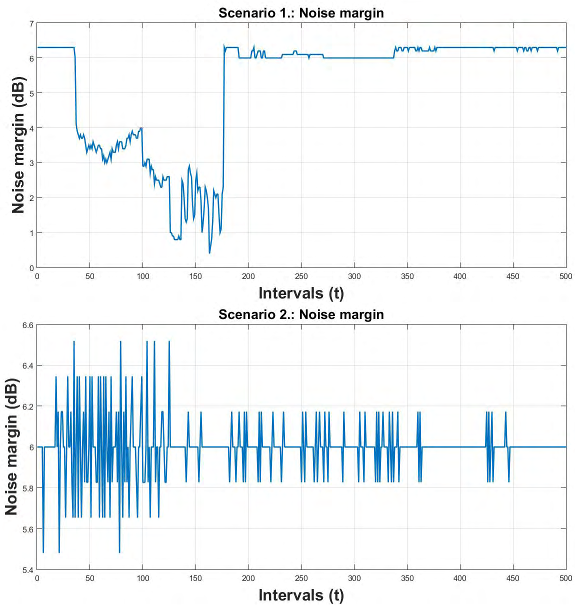

FIGURE 3. Noise margin values (in dB): a) for the first scenario and b) for the second scenario.

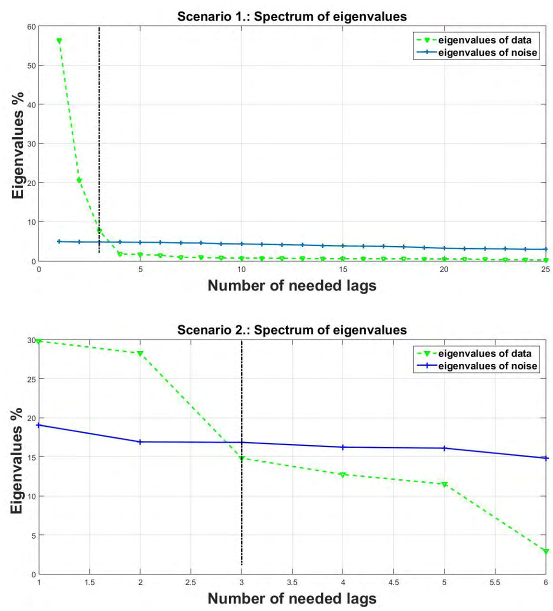

FIGURE 4. Spectrum of eigenvalues: a) for the first scenario and b) for the second scenario.

that produced instability of CQIs and video degradations. Simultaneously, the same video, without degradations, was captured on the other DSL line that had constant CQIs and therefore proper values of QoS indicators. CQIs, which are proposed in Technical Report TR-115 [59], are collected by system in which SELT had already been activated. The main CQI, which was observed during different time intervals, was NM (*Noise Margin*) and therefore, from its values, the base time series was created. Fig. 3 shows noise margin values (in dB) in different time intervals: a) for the first scenario and b) for the second scenario. SSA analysis was performed just on this parameter because we noticed the correlation between stability of noise margin and QoS. Other CQIs such as NumFECI (*Number of Forward Error Correction Indications*), Rc/Rs (*Relation between maximum and service line rate*), CV (*Code Violation*), ES (*Error Seconds*), PSD (*Power Spectral Density*) and INT (*Interleaving*) were used as input in DPCA block. Using mathematical formulation (3-28) and statistical analysis of CQIs the estimated values of QoS indicators were obtained.

Captured non-degraded video, completely same encoded as in the experiment (H.264 encoded, 25 fps, the same GOP), is recompiled in NS2 that was expanded by EvalVid. We created the same network structure in NS2 as in the experiment and provoked packet loss to disrupt QoS. The size of packet loss was actually equal to the values of estimated QoS and as a result, original video was degraded. We noticed that there was a bad correlation between original CQIs in both scenarios. Hence, using mathematical modeling is indispensable because of unclear correlation between original CQIs and QoS. In Fig. 4, the spectrum of eigenvalues for both scenarios was depicted. The spectrum of eigenvalues was obtained after SSA analysis of time series, composed by noise margin values. In this way, a number of needed lags for defining dynamics of time series was obtained.

Considering hypothesis from (12) and eigenvalues depicted on Fig. 4, it can be assumed that a few lagged series are needed for defining the order of the process in both cases. Upright lines that are obtained by (13-17) present the exact number of needed lags. This number defines the order of serial and parallel correlations in DPCA block as well as the number of needed vectors for creating Hankel matrix. After performing the SSA, Hankel matrix was formed by using (18) in DPCA block. In this block, PCA is being performed and as a result, a new **QoPH** vector space was obtained.

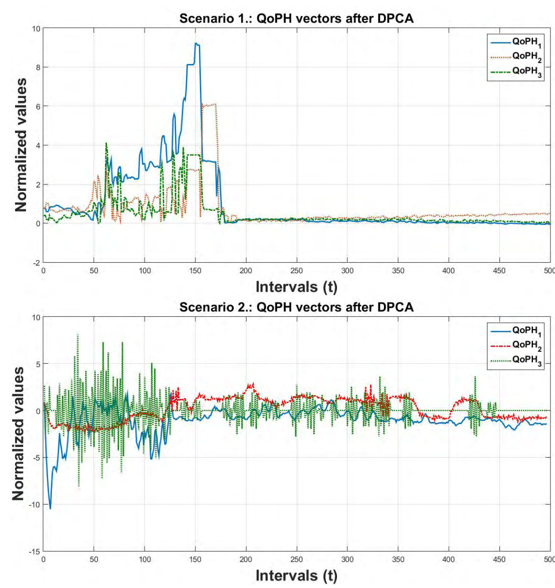

FIGURE 5. QoPH vectors: a) for the first scenario and b) for the second scenario.

Fig. 5 shows values of three **QoPH** normalized vectors obtained after PCA for the first and the second scenario. Hotelling's T^2 statistics, depicted in Fig. 6, is calculated by using (27) and only values that exceed the threshold defined

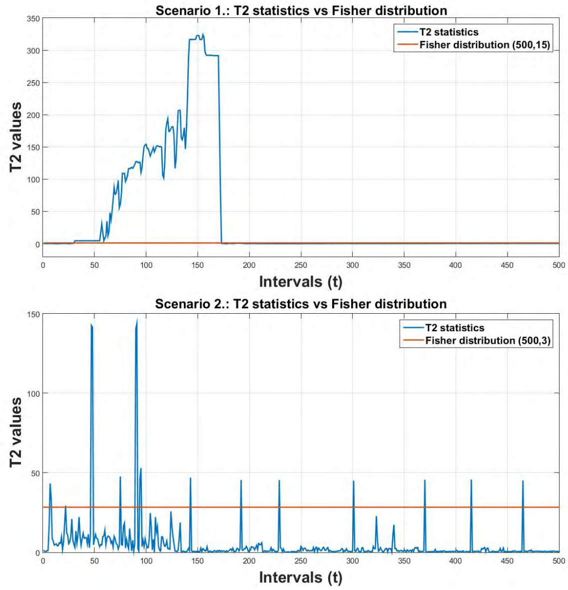

FIGURE 6. T2 Statistics vs. F-distribution.

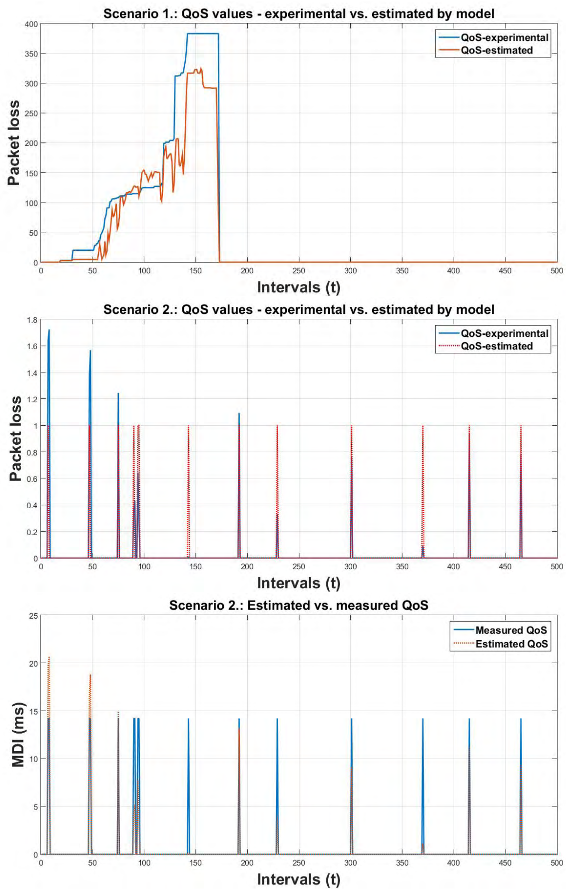

FIGURE 7. QoS indicator values: estimated vs. experimental.

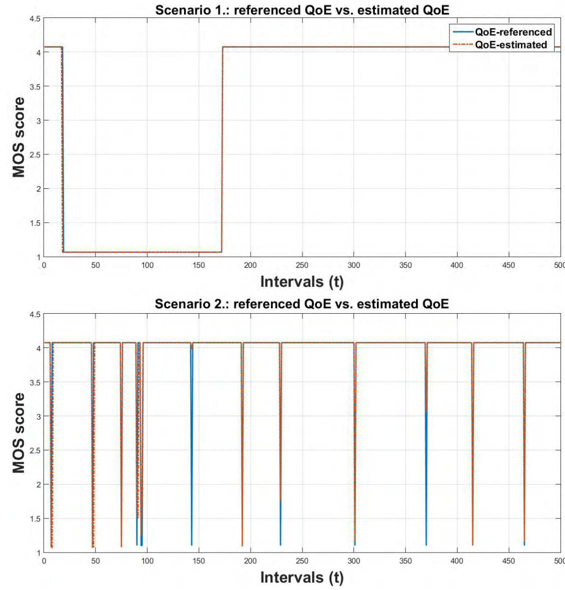

FIGURE 8. MOS values calculated by IQX hypothesis: referenced QoE (blue) vs. estimated QoE (orange).

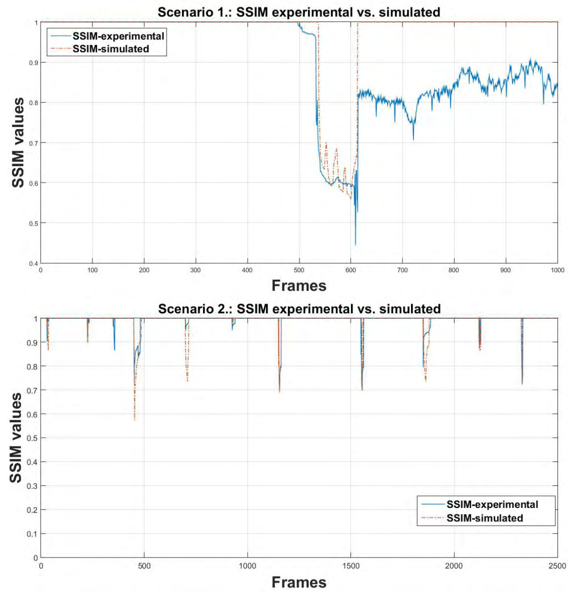

FIGURE 9. SSIM values calculated by comparing original, experimental and simulated video.

by F-distribution (red line) will be considered in the further analysis. Intervals in which those values will be taken into the further consideration are also depicted.

Considering Fig. 5 and Fig. 6, it can be clearly noticed that chosen vectors clearly illustrate process dynamics in the new vector space.

Fig. 7 depicts QoS_i values which are estimated by the mathematical model and the ones measured by QoS measuring instrument. Estimated QoS_i values are calculated by using b coefficients from (28-29) and chosen QoPH vectors. Previously, MLR analysis was performed between QoPH vectors and previous QoS indicator values to obtain b coefficients.

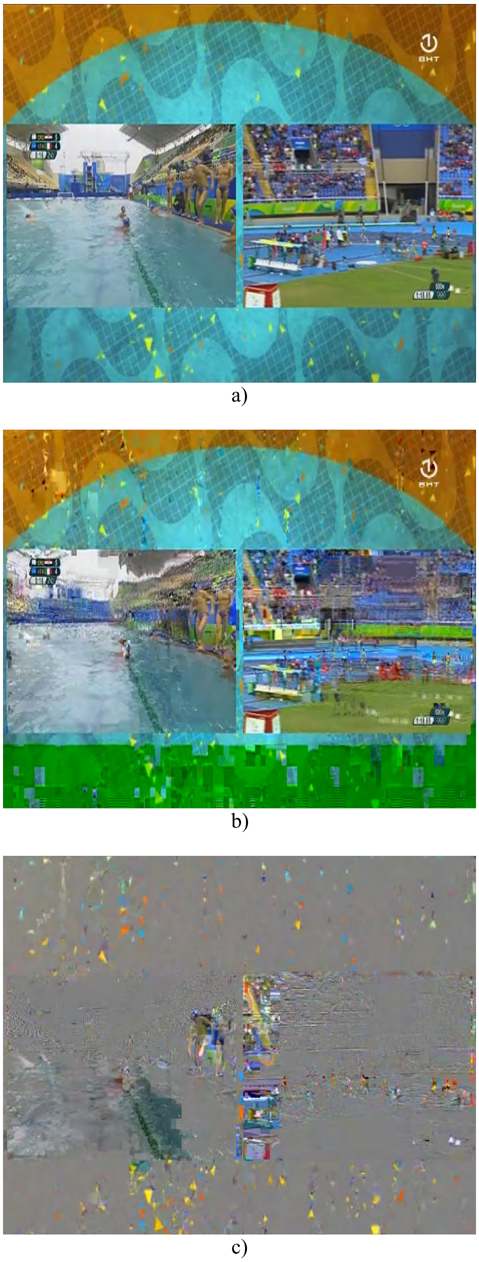

FIGURE 10. **The frame after the first degradation in Scenario 1. a) Original. b) Simulated case. c) Experimental case.**

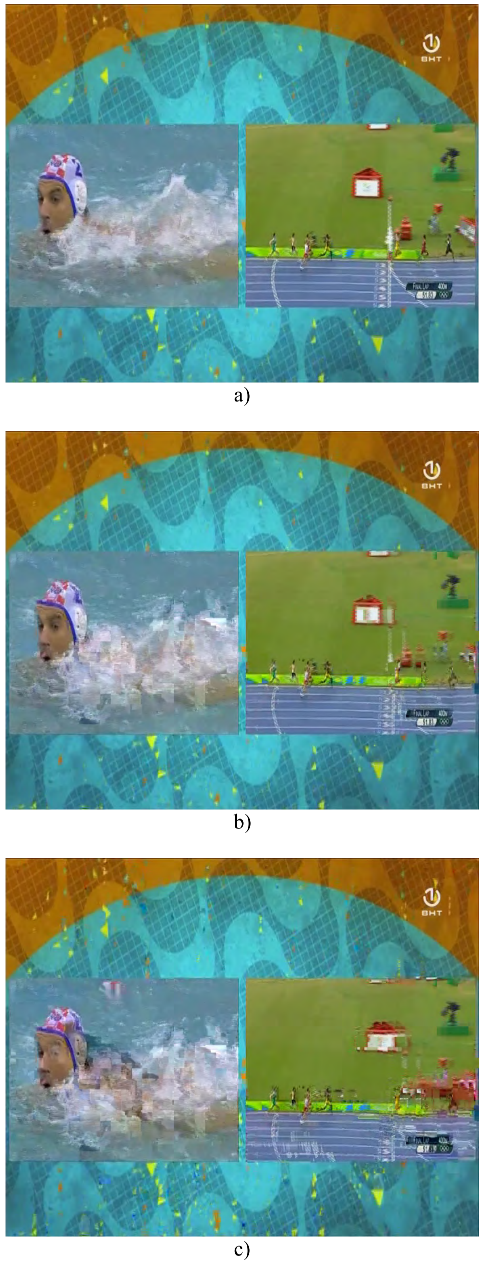

FIGURE 11. **The frame after the first degradation in Scenario 2. a) Original. b) Simulated case. c) Experimental case.**

Considering Fig. 7, the good correlation r can be noticed (r between 0.79 and 0.88) in both scenarios although there is a clear difference between estimated and measured QoS values. This can be explained by a difference between time resolution of DSL monitoring system and QoS based measuring system as well as using only a few QoPH vectors. QoS indicator MDI has completely the same values during disturbances in the first scenario while there are little differences in Fig 7 for the second scenario.

QoE values, depicted in Fig. 8, are calculated by analytical method shown in (30-32) which uses IQX hypothesis.

Estimated $\mathbf{QoS_i}$ values are used to calculate estimated MOS and on the contrary, QoS values measured by the instrument are used as reference MOS values.

As in the case of depicted $\mathbf{QoS_i}$ values, the same difference between estimated and measured QoE values can be noticed as well as their good correlation. For the purpose of additional QoE analysis, we have performed SSIM objective video test of particular frames in the case of both scenarios. According to [60], obtained SSIM values could be used for assessment of MOS. In the model, these values were obtained by comparing original (from non-degraded line) and degraded (from degraded line) video, and then original and simulated video. Considering Fig. 9, we can notice that after the first packet was lost, SSIM values decreased in both scenarios and in this moment there was a great correlation between simulated and experimental cases. However, after this phenomena there were no more lost packets, but in the first scenario, the experimental SSIM values were still different from 1 (which would be the expected value in the case of the absence of any degradation), although the video streaming was clearly non-degraded. The reason for this occurrence is the loss of synchronization among particular tested video frames. On the other hand, the graph in the simulated case has much smoother curves, which is in accordance to the real situation, because it shows that after packet loss stopped, the video returned to normal reproduction. Therefore, the first scenario shows that the simulation results are more accurate than the experimental ones. However, in the second scenario, there is a great correlation ($\overline{r_{SSIM}} = 0.98$) between the experimental and the simulated case. In this scenario, degradations were rare which allowed the video to return to normal reproduction. Video degradations, which appear in the first video frame, are depicted in Fig. 10. In the same figure, minor annoyance can be noted in the simulated case than in the experimental one. The reason for this is idealistic conditions in the simulated case. SSIM values, and consequently MOS values, were higher in the second scenario.

Hence, disturbances, caused by changing transfer function, corrupt the video less than disturbances caused by appearance of strong additional noise. Degradations in this case are depicted in Fig. 11. It is obvious, in this case, that degradations are less in both scenario. The general conclusion is that simulated case, in both scenarios, underestimates the size of the disturbance. In spite of this, there is a very good correlation between SSIM values, and the model can be used for approximate QoE estimation. Better analysis should be provided by dividing the video into smaller parts, which is left for further works.

IX. CONCLUSION

Statistical model, proposed in the paper, uses mathematical formalism in order to find the correlation between certain phenomena in the physical channel and disorders of QoS indicators. The model, in order to estimate QoS, monitors and analyzes CQI values, which can be collected during service delivering. Negative effects in the channel, caused by noise or changes of transfer function, decrease SNR. On the other hand, positive effects, created by error control system like FEC, cancel out the problem of SNR decreasing. The model takes into account both effects, as well as other parameters, and creates the QoPH vector space with maximum variance, which is affecting QoS. Consequently, by using analytical or objective assessment, which relates to NR (No Reference) or FR (Full Reference) method respectively, QoE values were estimated without user involvement in evaluation of service quality. The advantage of this model is being able to estimate QoS values and evaluate quality of the link from user to the first telecommunication node by observing only a set of physical parameters. Other benefits of this model can be used in cross-layer analysis and OPEX decreasing. It is very often, in DSL environment, to have a situation in which SNR level is normal, but service consumers complain that they have a problem. Presented practical model can find time interval in which a user had problems with the service, by applying procedure for time detection of negative dynamic changes. This can help the staff in making a decision when and where problem appeared and whether it is necessary to go out and check the situation in the field. Although the verification of the model was made in the DSL environment, it can be applied in wireless case by selection of different parameters, which are suitable for wireless media and that will be the subject of further research. Also expanding parameter set and considering their influence on multidimensional QoS arises as the necessity for future work.

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