Multipath Video Streaming Using GRA Network Ordering Algorithm without Rank Inconsistency

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Abstract—**Simultaneous connection to several networks through multiple interfaces is possible with today's mobile terminals. In order to efficiently utilize the interfaces' capabilities and increase the quality of the streamed video, multipath streaming can be used. Resource intensive applications can deliver high bitrate streams over multiple paths by cumulating the available bandwidth of the different subpaths. In this paper we propose a multipath streaming method that chooses a set of paths maximizing the overall quality at the client. While the available paths have different bandwidth, delay and loss probability constrains, the packet distributor must take the video packet importance and the dependencies between packets into account. In order to efficiently distribute the packets, the link must be ordered based on the network attributes. Grey Relational Analysis (GRA) is a promising algorithmic approach that can realize dynamic interface ordering with multiple alternatives (interfaces) and attributes (network parameters), however similarly to some other decision methods, GRA also suffers from rank reversal phenomenon. Transmitting the reference video frames on the most reliable links will decrease the loss probability of important data packets and increase the measured video quality. The change of link order can lead to frequent handovers causing the degradation of the observed video quality.**

Keywords – multipath streaming, QoS, Grey Relational Analysis, rank reversal

I. INTRODUCTION

The popularity of multimedia applications is increasing on the Internet in both wired and wireless environment. Despite the development of new wireless access technologies that provide higher bandwidth to the users, multimedia streaming applications still suffer from limited and highly varying bandwidth. However the offered bandwidth is getting higher, high quality video streams usually can not be transmitted on a single link. In order to utilize the advantages of the heterogeneous network model, mobile devices are now being built as multihomed multi–functioning wireless terminals. Multipath video streaming has recently been proposed as a solution to overcome the strict mobile network limitations. In order to increase the quality of streams using multihomed devices that have multiple network interfaces independently connected to different networks, the available interfaces must be effectively utilized. Higher bandwidth can be provided to the users if joint links are used. The independent but joint links can be successfully utilized by a streaming application in order to achieve high quality streaming.

In this paper an interface selection algorithm for multipath MPEG video streaming is presented. The missing packets in a video frame lead not only to reduced quality of the frame but also results the propagation of distortion to successive frames. This is due to inter–frame–video compression algorithms such as MPEG, which exploit temporal correlation between frames to achieve higher compression. The proposed scheme takes the video packet importance and the dependencies between packets into account and transmits the reference video frames on the most reliable links. Using the proposed packet distributor the loss probability of important data packets can be decreased, hereby increasing the measured video quality.

In our video multipath streaming proposal the available links must be ordered to determinate the best interfaces for the most important packets. The simplest ordering technique is to make the network ordering based on one network parameter, e.g. packet loss, however it is not the best solution. The network selection algorithm must depend on the requested services and other network parameters, such as throughput, delay, jitter, cost, signal strength etc. The ordering algorithm must be able to determine automatically the best interface and the interface order that fulfills the user's requirements.

Multi Attribute Decision Making (MADM) methods can be utilized for network ordering purposes. MADM algorithms are used for determining the ranking of alternatives in terms of their desirability with respect to multiple criteria that can influence the decision. The main goals of these solutions are to avoid frequent handover processes and offer acceptable QoS characteristics for different type of applications. In the recent years a new network selection method has been studied based on Grey System Theory [1]. The theory has been proven to be useful for dealing with poor, incomplete, and uncertain information. Grey Relational Analysis (GRA) is part of Grey System Theory, which is suitable for decision making with complicated interrelationships between multiple factors and variables. GRA has been successfully applied in network selection process as well [2]–[5]. Similarly to other MADM techniques, GRA has been also criticized for its possible rank reversal phenomenon, which means that the relative rankings of two decision alternatives could be reversed when a decision alternative is added or deleted. Rank reversal is a disadvantageous behavior even for our proposed content–aware multipath video streaming method. If not all the available links are used for the multipath transmission the network selection method, which automatically switches to the best network, may cause frequent handovers due to rank inconsistency. Each

appearance of a new network or a link disappearance may trigger a handover process increasing delay, causing gap in the transmission or even disconnecting the terminals.

In this paper we introduce a content–aware and multipath video streaming technique, which uses a modified GRA to make the ordering of links. We made innovation in both multipath streaming and GRA procedure. The main difference of our content–aware and multipath streaming technique from the other multipath streaming solutions is that we use a sender side buffer to heap up more data in order to utilize the available links more efficiently. We have analyzed the proposed multipath streaming scheme both analytically and with simulations to estimate the quality improvement of the transmitted video streams. Regarding to GRA procedure, used for network ordering, we propose a solution to eliminate the ordering inconsistency of GRA–based network selection algorithm. In order to avoid the effects of the rank reversal, we have analyzed the GRA–based network selection algorithm to found the reason of the phenomenon. We have found that modifying the normalization method, the probability of rank reversal can be significantly decreased or even eliminated. In order to justify our theoretical assumptions, we have examined the efficiency of the proposed solutions.

The rest of this paper is organized as follows. Review of related works in multipath video streaming and network selection decision methods, especially GRA technique are presented in Section II. In Section III we introduce our content–aware multipath streaming solution with sender side heap up buffer. Section IV describes our solutions for reducing and eliminating the rank reversal phenomenon for GRA–based network selection. The obtained performance results are presented in Section V. Finally, we summarize our paper and make the conclusions in the last section.

II. BACKGROUND AND RELATED WORKS

Our work combines the multipath video streaming and network ordering procedure, therefore in this section the previous studies of both techniques are introduced.

A. Multipath Video Streaming

Multipath multimedia streaming has become attractive solution due to its increased throughput and adaptive load balancing [6]. An overview of the benefits and use of path diversity for media streaming is introduced in [7][8]. In these works different approaches for media coding and streaming over multiple paths are examined, together with architectures for achieving path diversity between single or multiple senders and a single receiver. Novel solutions were also presented to improve the quality of streaming applications. The authors of [9][10] study video streaming using feedback–based reference picture selection schemes and path diversity. In [11] multipath streaming methods are examined from the application transparency point of view. A distributed sender–driven streaming solution is presented in [12], where servers collaboratively adapt to the network status in order to provide the media client with a superior video quality. Most of the related works analyze the multipath streaming solution using simulations; however the authors of [13] deployed a testbed for

the measurements. The multipath streaming was also investigated from congestion point of view in [14][15]. In the latter one, a fast heuristic–based algorithm is presented, built on load–balancing principles.

Multihomed protocols such as SCTP [16] provides the possibility of multiple link connections, however the current protocol version does not allow to use multiple path simultaneously. Ye et al. [17] introduced an independent per path congestion control principle for standard SCTP, while in [18] a similar solution is presented with load sharing techniques.

B. Network Ordering

Neither of the previously developed multipath streaming schemes deal with ranking of links, however it plays an important role in each proposal. In our solution GRA (Grey Relational Analysis) was used for this purpose, which is one of the Multi Attribute Decision Making (MADM) techniques.

Numerous network selection methods were studied in the past decade. All these decision algorithms are used for determining the ranking of competitive network access possibilities and making the best choice for the user. In the traditional methods such as [19]–[22], only the radio signal strength (RSS) threshold and hysteresis values are considered. The simple RSS–based decision is not sufficient because it does not take into account the provided services and features of different access technologies.

Making the decision based on one parameter is usually inadequate, therefore MADM algorithms such as SAW, TOPSIS, AHP (Analytic Hierarchy Process), ELECTRE, etc. have been developed and described in [22]–[29]. These solutions determinates the preferred network using technology specific features such as bandwidth, delay, packet loss probability, cost of network usage, etc. Roveri et al. [30] used weight factors to reflect the dominances of the particular requirements with respect to the user. GRA–based (Grey Relation Analysis) network selection method [2]–[5] is an alternative technique for determination of the network priority order. Similarly to TOPSIS and some ELECTRE variants, GRA also suffers from rank inconsistency.

A robust MADM algorithm must ensure that the order of alternatives does not change when an alternative, which is not the best, is removed or replaced by another alternative. Therefore, if an algorithm suffers from the ranking abnormality problem, the ranking order is not stable.

1) Grey Relational Analysis (GRA)

Grey System Theory was introduced in [1] to analyze the relational grade for several discrete sequences and select the best sequence. One of the sequences is defined as reference sequence presenting the idea situation. The grey relationship between the reference sequence and the other sequences can be determinated by calculating the Grey Relational Coefficient (GRC) according to the level of similarity and variability. The technique is appropriate and effective for network selection purposes as well. The GRA–based network selection method can be implemented following the steps bellow:

1. Classifying the network parameters (*lower–the–better*, *higher–the–better*)
2. Defining the upper and lower bounds of the parameters
3. Normalizing the parameters
4. Calculating the Grey Relational Coefficient (GRC)
5. Ranking the networks according to the GRC values

To calculate the GRC, the network parameters must be categorized first. For delay, cost, etc. parameters the *smaller–the–better* class is used, while the e.g. throughput and signal strength parameters belong to the *larger–the–better* category. Before calculating the GRC for each parameter of the network, the series data need to be normalized to eliminate dimensional units. Assuming that n possible networks (S_1, S_2,…, S_n) are compared, and each network has k parameters, the upper bound (u_j) is defined as max$\{s_1(j), s_2(j), ..., s_n(j)\}$, and the lower bound ($l_j$) as min$\{s_1(j), s_2(j), ..., s_n(j)\}$, where $j = 1,2,…,k$. In case of *smaller–the–better* attribute, the normalized value of $s_i(j)$ parameter can be calculated as follows:

$$s_i^*(j) = \frac{u_j - s_i(j)}{u_j - l_j} \qquad (1)$$

Similarly, the normalized value of a *larger–the–better* parameter:

$$s_i^*(j) = \frac{s_i(j) - l_j}{u_j - l_j} \qquad (2)$$

The attributes of a network can be represented as a row matrix, where the elements of the matrix are the normalized values of k different network attributes.

$$S = \begin{bmatrix} s^*(1) & s^*(2) & s^*(3) & ... & s^*(k) \end{bmatrix} \qquad (3)$$

While $s_i^*(j)$ parameters are maximized in 1, the most preferable network can be always described as $s_i^*(j) = 1$, where $j = 1,2,…,k$ and k is the number of network parameters used for the decision. Utilizing this behavior of the normalizing algorithm, the ideal network is considered as $S = [1\ 1\ …\ 1]$.

If there are N competing networks to choose from, the previous row matrix (3) can be extended to an $N \times k$ matrix, which contains all the parameters that plays role in the network selection procedure. The matrix can be determined as follows:

$$S_N = \begin{bmatrix} s_1^*(1) & s_1^*(2) & s_1^*(3) & ... & s_1^*(k) \\ s_2^*(1) & s_2^*(2) & s_2^*(3) & ... & s_2^*(k) \\ ... \\ s_N^*(1) & s_N^*(2) & s_N^*(3) & ... & s_N^*(k) \end{bmatrix} \qquad (4)$$

The final step of the GRA–based network selection algorithm is to calculate the Grey Relational Coefficient (GRC). The value of the GRC parameter is calculated by the following equation, where w_j is the weight of each parameter and i ($1 \leq i \leq N$) is the network index:

$$GRC_i = \frac{1}{\sum_{j=1}^{k} w_j \left| s_i^*(j) - 1 \right| + 1} \qquad (5)$$

The network with the largest GRC is the most desirable one.

2) Rank Reversal Phenomenon in MADM algorithms

Most of the MADM–based ranking algorithms use normalization and upper/lower bounds determinations of the network parameters. Rank reversals in the SAW, TOPSIS, AHP, GRA methods are caused by the changes of normalized attribute values. Some proposals [27],[31] were presented to avoid rank reversal in AHP and TOPSIS, while Barzilai and Golany [32] have proved that no normalization can prevent rank reversal. However, normalization is often necessary for most of the MADM approaches to eliminate different dimensional units. GRA also suffers from the rank reversal as the following example shows. The attributes and its normalized values used for the network selection decision are shown in Table I.

TABLE I.   GRA–BASED NETWORK SELECTION DECISION

Network	Delay		Jitter		Loss rate		Throughput		Cost	
	GRC	ms	norm	ms	norm	ratio	norm	Mbps	norm	$/MB	norm
#1	0.339	10	1	8	1	0.112	0	10	0.79	1	0.978
#2	0.304	200	0	10	0.916	0.01	0.913	80	0.885	10	0
#3	**0.343**	100	0.526	21	0.458	0.1	0.107	90	1	0.8	1
#4	0.281	50	0.789	32	0	0.0003	1	4	0.01	4	0.652
#5	0.302	160	0.21	12	0.833	0.012	0.916	3	0	3	0.76

According to the normalization equations (1) and (2) of the GRA–based decision making, we can found 0 and 1 normalized values for each network attribute. Normalized value 1 means that the network offers the best performance from the given parameter point of view, while 0 means the opposite. By calculating the GRC (5) the ranking order can be determinated. In the example presented in Table I, network #3 is the best choice and #2 is the worst one, if the weights of the attributes are considered equal.

Supposing that the worst network (#2) is not reachable any more, the normalized values and calculated GRCs will be changed as Table II. shows.

TABLE II.   GRA–BASED NETWORK SELECTION DECISION WITHOUT NETWORK #2

Network	Delay		Jitter		Loss rate		Throughput		Cost	
	GRC	Ms	norm	ms	norm	ratio	Norm	Mbps	norm	$/MB	norm
#1	**0.335**	10	1	8	1	0.112	0	10	0.079	1	0.937
#2		--	--	--	--	--	--	--	--	--	--
#3	0.329	100	0.4	21	0.458	0.1	0.107	90	1	0.8	1
#4	0.234	50	0.733	32	0	0.0003	1	4	0.01	4	0
#5	0.252	160	0	12	0.833	0.012	0.891	3	0	3	0.312

After the removal of network #2 the best network was changed to network #1, however the network parameters were not changed.

III. CONTENT–AWARE MULTIPATH STREAMING

We consider a client–server network topology, where the client can access the server simultaneously through different paths. The independent paths are characterized with different bandwidth (bw_i), packet loss ratio (p_i), network delay (d_i), etc. parameters belonging to path i.
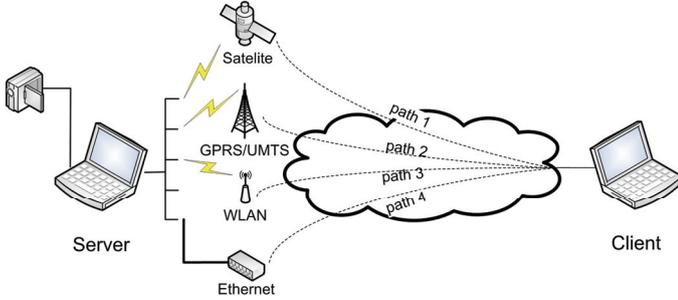
Figure 1. Multipath data delivery

Network delay parameter plays role when a strict playout buffer is used at the receiver. If the transmitted packet is received after the playout time, it can be considered as lost packet, therefore we do not deal with the delay parameter separately. We consider that total packet loss probability (π_i) on path i contains the loss events due to channel errors and late reception of video packets:

$$\pi_i = p_i + \Pr(d_i > d_{pbuff}), \qquad (6)$$

where d_{pbuff} is the playout buffer delay. The overall packet loss ratio for the multipath transmission is the weighted average of the total packet loss probabilities

$$\pi = \frac{d_1}{d}\pi_1 + \frac{d_2}{d}\pi_2 + ... + \frac{d_n}{d}\pi_n = \sum_{i=1}^{n}\frac{d_i}{d}\pi_i \qquad (7)$$

where d_i is the data amount transmitted on link the ith link and d is the total size of the delivered video stream.

The transmitted video quality can be increased if the total packet loss probability is minimized; therefore the available paths are used in order of the links quality (π_i). The lowest packet loss ratio paths must be utilized first and the worst channels must be used only if necessary. The impact of packet loss ratio is the most significant, however other network attributes must be also considered for the network order determination. For example the physical parameters of a link can be very good, but if the [$/byte] cost of usage is extremely high, the link will not be chosen. The cost has no impact on the video quality, but it can be an attribute of the network order decision algorithm.

Further video quality improvement can be achieved if the packet contain is also taken into account. The MPEG coded video streams use different frame types (I–, P– and B–frames) with inter–frame dependencies. We propose a content–aware packet distributor scheme in order to minimize the distortion propagation in the stream by forwarding the I–frames on the most reliable links.

In our proposed scheme a buffer is applied that heaps up B_f number of frames causing d_B extra delay. In every d_B time we distribute the stored data packets between the interfaces and the heap up procedure starts again. This method makes it possible to efficiently distribute the data packets of the video stream. If longer delay (d_B) is used, more I–frames can be forwarded to the most reliable link, but the overall delay (D) will be also higher.

$$D = d_B + \max_i(d_i) \qquad (8)$$

The acceptable delay threshold depends on the used multimedia application. In case of one–way live media applications it can be even few seconds, but if two–way interactive application is used the perceptual tolerance of the user is around 150–200ms. The limitations of two–way interactive applications are too strict for our proposed interface selection algorithm, but for pre–recorded and one–way live video streams this solution is acceptable from the delay point of view.

The streaming server is connected to the channels through buffer interfaces, which are modeled as FIFO queues. These queues are refilled at every d_B time from the heap up buffer. The interface buffers' sizes are determinated by the paths bandwidth and the heap up buffer delay (d_B). The interface buffers must be purged in d_B time to be able to receive the next amount of data. The server side interface selection scheme is illustrated in Figure 2.

The video quality improvement is gained due to the efficient packet distribution from the heap up buffer to the interface buffers. Due to the proposed content–aware interface selection method the distribution of data belonging to I–, P–, B–frames on the independent links will be totally different from the original video frame structure. On the reliable channels more I–frame data will be delivered and less B–frames, while on links with high loss probability mostly B–frames will be transmitted.
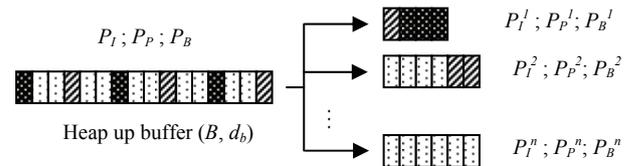
Figure 2. Frame distribution on the interfaces

The possibility of the data bytes belonging to I–, P– and B–frames of the video stream is consequently P_I, P_P and P_B. If the heap up delay (d_B) is long enough these possibilities are similar in the heap up buffer. Due to the proposed interface selection algorithm the distribution of I–, P–, B–frame data bytes in the interface buffers will be different from the original video frame data distribution.

The possibility that a data byte belongs to an I–frame in the most reliable interface's buffer can be calculated as follows:

$$P_I^1 = \min\left(\frac{P_I B}{b_1}, 1\right) \qquad (9)$$

Parameter B is the size of data heaped up, while B_I is the buffer size of the first (most reliable) interface. We use the *min*() function to keep the probability variable bellow or equal to 1.

In order to analyze the behavior of the proposed scheme we can calculate the distribution of I–, P–, B–frame data bytes in the interface buffers (P_I^i, P_P^i and P_B^i). The I–frame data probability in the ith interface buffer is:

$$P_I^i = \max\left(0, \min\left(\frac{P_I B - \sum_{n=1}^{i-1} b_n}{b_n}, 1\right)\right) \qquad (10)$$

Similarly, the P– and B–frame data ratios in the ith interface buffer can be calculated as follows:

$$P_P^i = \max\left(0, \min\left(\left(\max\left(0, \min\left(\frac{P_P B - \sum_{n=1}^{i} P_P^n b_n}{b_n}, 1\right)\right) - P_I^i\right), 1\right)\right) \quad (11)$$

$$P_B^i = \max\left(0, \min\left(\left(\max\left(0, \min\left(\frac{P_B B - \sum_{n=1}^{i} P_B^n b_n}{b_n}, 1\right)\right) - P_I^i - P_P^i\right), 1\right)\right) \ (12)$$

The video quality depends on the number of lost packets and on the content of the missing packet. The loss of a B–frame packet will not reduce the quality so significantly than an I–frame loss, due to frame dependencies of the MPEG video stream structure. The aim of the proposed scheme is to reduce the I– and P–frame data losses.

The number of lost I–, P– and B–frame packets can be estimated based on the link packet loss probability (π_i) and the previously introduced frame ratio ratios on the links, see equations (10)–(12). Considering that the interfaces are ordered according to the links' packet loss ratio ($\pi_1 \leq \pi_2 \leq \ldots \leq \pi_n$) the number of lost packet, which contains I–frame data, can be calculated as follows:

$$N_I = \sum_{i=1}^{n} \frac{P_I^i b_i}{S} \pi_i \qquad (13)$$

The packet size is signed with S, while b_i stands for the buffer size of the ith interface. Similarly to (13), the number of P– and B–frame packet losses can be also estimated.

In this section the effect of packet loss ratios was studied as the primary network parameter. The packet probability and the delay have the most significant impact on the video quality, where the late packets are handled as lost packets. In our investigations the packet losses due to late delivery were not distinguished, therefore we did not need to separately handle the delay parameter.

Besides the loss ratio, numerous other network parameter can be used to determinate the interface order. Some of these

parameters, such as cost, link availability ratio, etc. have no immediate impact on the video quality, however these type of parameters must be also taken into consideration.

IV. ALTERNATIVE NORMALIZATION METHODS FOR GRA– BASED NETWORK SELECTION

Grey Relational Analysis (GRA) is an effective tool for network ordering purposes. Similarly to other solutions GRA also suffers from rank reversal phenomenon. It can be easily proved that the reason of this observable fact is the normalization method. The result of the Grey Relational Coefficient (GRC) equation (5) will change only if the normalized network attributes also changes, however we assume that the network parameters are constant.

Although the network parameters, such as bandwidth, delay, loss rate, etc. is considered constant, the normalized value of these attributes can be changed if one of the network is not reachable any more. This can be happen if one of the disappearing networks attribute has the highest or lowest value. In this case the attribute order will not change of course, but the distance between the normalized values may vary significantly as the example shows bellow.
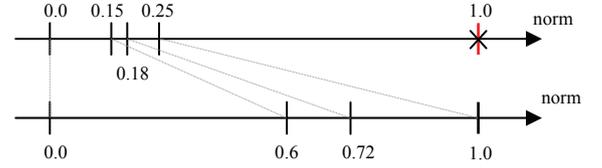
Figure 3. The effect of removing the highest value on the normalized value

As the figure presents that the normalized values calculated with equation (1) and (2) significantly differ, when the highest element was removed. While the difference between the two normalized value in the middle is only 0.18-0.15=0.03, after the removal of the highest attribute, the difference becomes 0.72-0.6=0.12. However the real data was not changed, the significant variance of the normalized values can modify the rank order of the networks.

Our main goal was to reduce the effect of the normalization on the rank order. We propose three different methods to replace the actual normalization procedure described by equations (1) and (2).

Our first normalization solution keeps the normalized values unchanged by determinating absolute min–max values of an attribute. By keeping the normalized values unchanged the calculated GRC will be the same even if a network is not reachable any more, therefore the rank reversal phenomenon is eliminated. The modified normalized value of a *smaller–the–better* attribute can be calculated as follows:

$$s_i^*(j) = \frac{E_{max\,j} - s_i(j)}{E_{max\,j} - E_{min\,j}} \qquad (14)$$

Similarly, the normalized value of a *larger–the–better* parameter:

$$s_i^*(j) = \frac{s_i(j) - E_{min\,j}}{E_{max\,j} - E_{min\,j}} \qquad (15)$$

Variable $E_{min\,j}$ and $E_{max\,j}$ stands for absolute minimum and maximum of the jth network parameter. The jth parameter value therefore must be always between $E_{min\,j}$ and $E_{max\,j}$. For the absolute minimum $E_{min\,j} = 0$ can be an adequate option, while for the absolute maximum ($E_{max\,j}$) the given network attribute behavior must be analyzed.
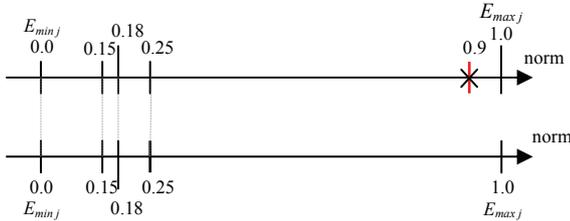
Figure 4.   Preventing normalized value changes, using absolute min–max attributes

The second modified normalization method is similar to the previous one, but it uses absolute bound only in the unwanted direction of an attribute. In case of *smaller–the–better* attribute an absolute maximum is determinated, while for *larger–the–better* parameter an absolute minimum is used. The reason of this solution is that usually those networks are becoming unreachable which attributes are bad. For example, in case of *larger–the–better* attribute (e.g. signal strength, throughput) that network will disappear which signal strength and/or throughput become very low. A network with high signal strength and throughput probably will not become unreachable, therefore need to use only absolute minimum in these cases, in order to reduce the rank reversal probability.

According to previous assumption, the modified normalized value of a *smaller–the–better* attribute can be calculated as follows:

$$s_i^*(j) = \frac{E_{max\,j} - s_i(j)}{E_{max\,j} - l_j} \qquad (16)$$

Similarly, the normalized value of a *larger–the–better* parameter:

$$s_i^*(j) = \frac{s_i(j) - E_{min\,j}}{u_j - E_{min\,j}} \qquad (17)$$

In the equations $E_{min\,j}$ and $E_{max\,j}$ is the absolute minimum and maximum of the jth network parameter that must be determinated before the network selection procedure starts. Variable u_j is the maximal value of the jth parameter, and it is defined as $\max\{s_1(j), s_2(j), ..., s_n(j)\}$. The lowest value ($l_j$) is defined as $\min\{s_1(j), s_2(j), ..., s_n(j)\}$.

The secondly introduced normalization technique will not eliminate rank reversal, because normalized value of a parameter can still change if the best network becomes unreachable. We can assume that in most of the cases the best network will not disappear unexpectedly, therefore the normalized values and the calculated GRC probably will not be

changed. Using this way of normalization, neither the normalized value of the best attribute will be equal to 1, nor will the normalized value of the worst attribute be equal to 0.

In our third normalization solution our aim was to avoid the usage of absolute min–max values. Similarly to the previous solution we proposed that those networks will become unreachable which parameters are worse. We have constructed the normalization function in such a way that the normalized value of the best parameter be equal to 1.

The proposed normalization function of a *smaller–the–better* attribute is as follows:

$$s_i^*(j) = \frac{l_j}{s_i(j)} \qquad (18)$$

The normalized value of a *larger–the–better* parameter can be calculated similarly:

$$s_i^*(j) = \frac{s_i(j)}{u_j} \qquad (19)$$

In the equations u_j stands for the maximal value of the jth parameter defined as $\max\{s_1(j), s_2(j), ..., s_n(j)\}$, while l_j is the lowest value.

This normalization technique guarantees that the best attribute will be 1, therefore the distances between the normalized values of an attribute will be higher compared to the secondly introduced normalization technique. The ranking order will be clearer, because the differences of the calculated coefficients (GRC) belonging to different networks will be bigger. The third normalization technique will not solve the rank reversal problem, however it significantly reduces its occurrence probability. To calculate the normalized value of a *smaller–the–better* attribute (18) we use only the lowest from the examined parameters (l_j) that is considered as the best choice from the jth parameter point of view. Therefore the removal of any other network, but not the best one, will not cause the change of the normalized values. The calculation of the normalized values of the *larger–the–better* parameters (19) is similar, but in these cases the highest value of the jth parameter (u_j) is used. The normalized values will change only if the network which jth parameter equal to u_j is removed.

V.   PERFORMANCE EVALUATION

This section presents and discusses the performance of the proposed algorithms regarding to content–aware packet distribution and modified GRA network ordering technique.

A.   Multipath Video Streaming

This subsection compares our content–aware interface selection solution to *continuous* and to *balanced* interface selection methods. The *continuous* method fills the interface buffers continuously from the video source or the video data storage. This model does not use heap up buffer, therefore the advantage of this method that no extra delay is introduced. We consider that the links are ordered and the most reliable link buffer is filled first and if the link's capacity is fully utilized, the next interface is selected and so

on. The distribution of different frame type data on the links will be similar to the original video frame structure ($P_I : P_P : P_B = P_I^i : P_P^i : P_B^i$). Previous works does not apply heap up buffer, hence the actual frame data must be forwarded to the link buffers immediately. The *balanced* method fills the interface buffers uniformly, using the Round–Robin model. If of one of the interface buffer is full, the remained video data is distributed between the other interfaces, which are not full yet. This Round–Robin based interface selection method does not take the link characteristics into account. The distribution of the video frame type data in the interface buffers will be similar to the original frame structure ($P_I : P_P : P_B = P_I^i : P_P^i : P_B^i$).

We have developed a simulation tool to analyze the behavior of the proposed content–aware interface selection scheme. Each simulation scenario was executed ten times and an average was calculated from the obtained results. The *mother_and_daughter* QCIF sequence was used as the reference video. The video sequence was compressed with an MPEG–4 encoder – *ffmpeg [35]*. The video stream was coded at 25 fps and 300kbps. The frame structure is specified by the *N*=10 and *M*=5 parameters. *N* and *M* are the intraframe and interframe coding ratios, which define the sequence of I–, P– and B–frames. *N* specifies the I–frame interval whereas *M* determines the I– or P–frame interval. The distribution of the used video data bytes belonging to I–, P– and B–frames is P_I=51%, P_P=20% and P_B=29%. In the analyzed test scenarios six links were applied with different characteristics. The link properties (bandwidth and loss ratio) used in the simulations are given in the next table.

TABLE III.   LINK PROPERTIES

Link no.	Bandwidth [kbps]	Packet loss ratio
1	100	0.0
2	80	0.001
3	80	0.005
4	60	0.01
5	60	0.01
6	20	0.05

The first point of our performance examinations was to analyze the link utilization ratio. We have examined how the proposed interface selection method utilizes the available resources. In our method a heap up buffer is used to collect definite number of frames (causing definite delay). When more data is collected in the heap up buffer, the packet distributor can be more effective, because it can found frames with small sizes, which can still fit to the nearly full interface buffer. In the first test scenario we have compared the link utilization of the proposed method with different heap up buffer sizes. The smallest examined buffer size was able to store 20 frames, which is equal to 0.8 seconds delay, while the biggest heap up buffer had 160 frames (d_B=6.4s).

The results show that setting the heap up buffer high, the usage of most reliable channels is also higher, while the load of less reliable ones is lower compared to other heap up buffer settings. For example, when the packets are distributed from a 160 frame sized heap up buffer, the worst link with number 6 is even not used, because the packet distributor could found free gaps in the interface buffers more efficiently and filled the reliable link buffers. Some of the links are barely used, while on the best links signed with number 1 to 3 (Table III.), closely the entire bandwidth is used. The utilization level of the links varied in time, because the heap up buffer level was also varying. The heap up buffer load is determinated by the number of frames (or delay) and not by the data size, therefore the data amount size in bytes can also change in time. Low level of utilization was measured on links with number 4–6 (Table III.). This is due to average calculations, because the worst links are not used when the actual heap up buffer level is low. Similarly, if the current heap up buffer size is high, all the links are used.

After the link load measurements the MPEG frame type distribution in the interface buffers was analyzed. The performance of the proposed content–aware interface selection scheme depends of the video frame distribution on the links with different characteristics. Our aim is to deliver the I–frame data packets on the most reliable channels and transmit the P– and B–frames on the reliable links if the link capacity is sufficient. Figure 5. illustrates the different frame type distributions in the interface buffers. In the analyzed scenario the heap up buffer size was set to 80 frames, which is equal to d_B=3.2s heap up delay. The interfaces are numbered based on the packet loss ratios and ordered, so the interface which uses the most reliable link has number 1, while the link with the highest drop probability has number 6. The video bitrate is 300kbps and the I–frame data ratio of the MPEG–4 video stream is P_I=51%, hence the I–frame data bandwidth requirement is about 150kbps.

a) I—frame distribution on the interfaces   b) P—frame distribution on the interfaces   c) B—frame distribution on the interfaces
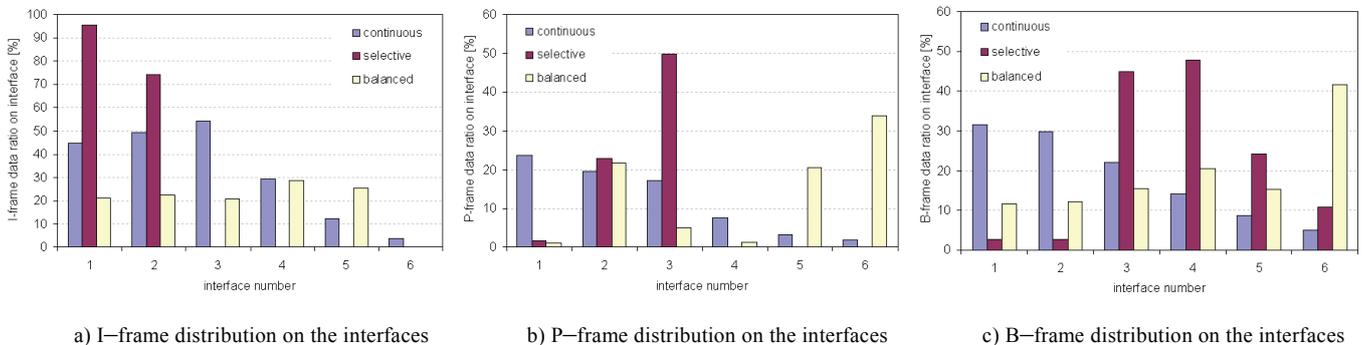
Figure 5.   Different frame type distributions in the interface buffers

As the presented results show I–frame data can delivered on the first two interfaces (100kbps+80kbps) when the proposed content–based selective packet distributor algorithm is used (Figure 5. a.). Most of the P–frames were delivered on the 3th interface, while the B–frames were transferred on the less reliable channels. Due to this ordered packet delivery the number of lost packets belonging to I–frames is estimated to be significantly lower then the number of other frame packet losses.

The observed video quality highly depends on the number of lost packets and the packet content. In order to analyze the behavior of the proposed multipath delivery method we have examined the different frame type data packet losses. The overall packet loss ratio was also measured, which is the average of the I–, P– and B–frame packet loss ratios. The results are presented in Figure 6. Similarly to the previous measurements the heap up buffer size was set to 80 frames.
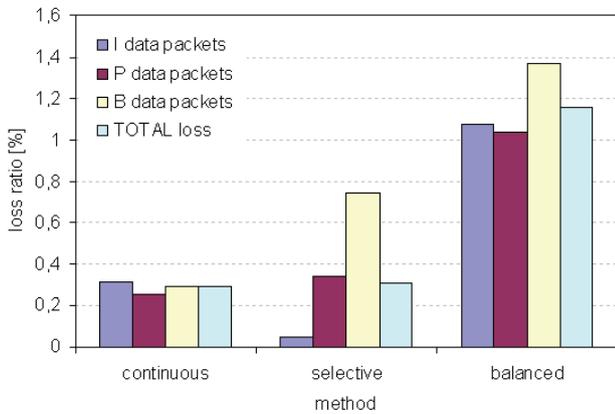
Figure 6. Total and I–, P–, B–frame type data packet loss ratios

As we expected, the total number of packet losses was equal using the continuous packet distributor method and the selective one. In spite of the similarity the number of I–frame data packet losses was significantly lower when the proposed interface selection algorithm was used. In case of the continuous algorithm the loss probabilities of different type of frame data was near equal, however protecting the I–frame data the error propagation can be prevented, hence video quality improvement can be achieved. The worst method is the balanced one as Figure 6. shows, because in this case the packet distributor equally fills the buffers belonging to reliable and unreliable channels.

The main goal of our proposal is to improve the quality of video streams. To see the effectiveness our scheme we measured the average peak signal–to–noise ratio (PSNR) of the transmitted video stream with different heap up buffer size setups. The PSNR values were measured against the original frames applying the content–aware interface selection scheme, the continuous and the balanced method. As it was expected, the measured PSNR value dropped dramatically when the packet loss increased.
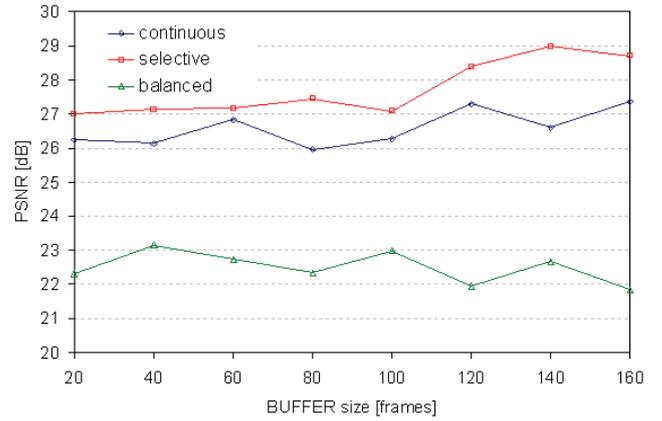
Figure 7. Average PSNR measured with different heap up buffer size setups

The video quality difference between the selective and continuous scheme was not so significant because the total packet loss ratio in case of the two schemes was similar. The performance of the balanced method is very poor. When only the link loss probabilities were taken into consideration (*continuous* method) the video quality was acceptable. When the packets are distributed based on its content, further quality improvement was achieved. The difference was about 1dB in our tests, but of course it can vary significantly according to the link properties and the coded video sequence.

B. Modified GRA–based network selection method

In Section IV three different normalization techniques for GRA–based network selection decision was presented. Table IV summarizes the original and the proposed solutions.

TABLE IV.   NORMALIZATION TECHNIQUES FOR GRA–BASED NETWORK SELECTION

	original	norm_1	norm_2	norm_3
smaller-the-better	$\dfrac{u_j - s_i(j)}{u_j - l_j}$	$\dfrac{E_{max\,j} - s_i(j)}{E_{max\,j} - E_{min\,j}}$	$\dfrac{E_{max\,j} - s_i(j)}{E_{max\,j} - l_j}$	$\dfrac{l_j}{s_i(j)}$
larger-the-better	$\dfrac{s_i(j) - l_j}{u_j - l_j}$	$\dfrac{s_i(j) - E_{min\,j}}{E_{max\,j} - E_{min\,j}}$	$\dfrac{s_i(j) - E_{min\,j}}{u_j - E_{min\,j}}$	$\dfrac{s_i(j)}{u_j}$

In order to analyze the efficiency of different normalization methods from the rank reversal phenomenon point of view, we have implemented a simulator tool. Rank reversal depends on the network parameters, disappearing network and normalization method. To compare the different solutions, we have analyzed the frequency of rank order changes caused by network removals. The highest probability of rank reversal can be reached if the worst network is removed, likewise the disappearance of the worst network is the most realistic.
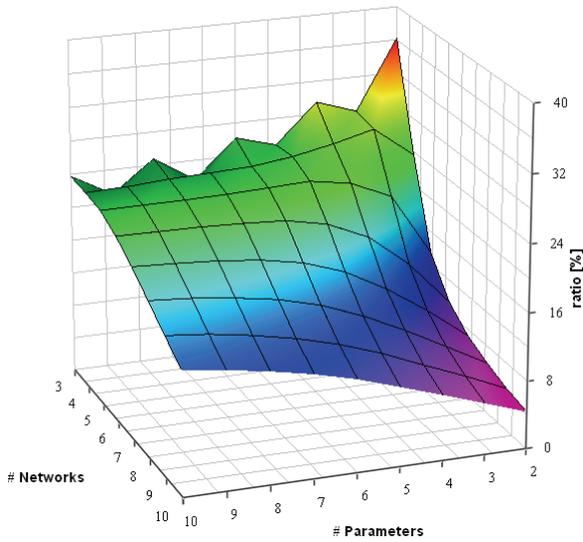
a) original GRA–based network selection decision
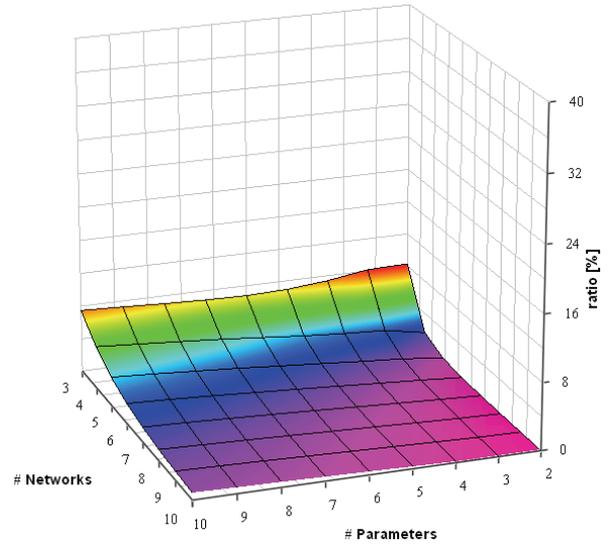
b) of GRA–based network selection decision with
norm_2 normalization technique

Figure 8.   Rank reversal probability

In our simulator tool we used random variables as network parameters. According to the defined steps of the GRA method, we have normalized the network parameters (*original, norm_1, norm_2, norm_3*) and calculated the GRC (Grey Relational Coefficient). As next step we removed the worst network (network with the lowest GRC) and started the GRA process from the beginning. As last step we checked whether the selected network before and after the removal is the same.

We have iterated the described simulation method 10^6 times in order to have statistically correct results. The ratio of total number of iterations and the number of different decisions was calculated, that can be considered as the probability of rank reversal. Figure 9. shows the obtained results.
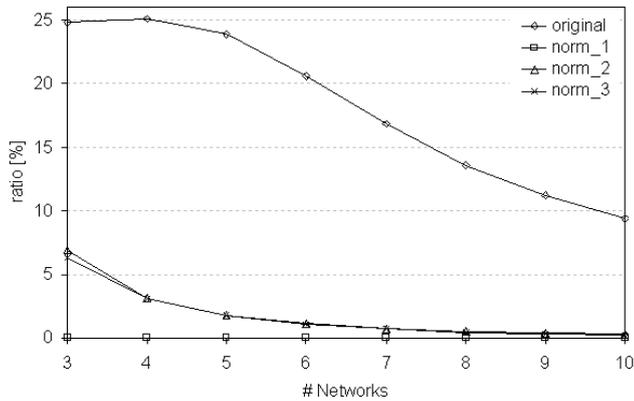
Figure 9.   Measured rank reversal probability in case of 5 network attributes

The number of networks in the simulation was 3 to 10, while the number of network parameters was 5. As the results show the original GRA performance was very bad. In the cases when 5 or less networks were reachable and the worst network was removed, the probability of rank reversal was about 25%. Compared to the original GRA method, our techniques (*norm_2*, *norm_3*) reduced the rank abnormality by 65% to 99.9% as Figure 9. shows. Using normalization method with absolute min–max values (*norm_1*), the rank reversal phenomenon was eliminated. With *norm_2* and *norm_3*, the probability that the best network will change after the worst network removal is significantly lower. The performance of *norm_2* is very similar to *norm_3* technique.

As it can be observed, the number of accessible networks has impact on the rank reversal probability. By increasing the number of available networks the analyzed ratio decreases, because the probability that the maximal (u_j) and minimal (l_j) values will change is lower, when the worst network is removed.

We have analyzed the relation between the number of parameters and the rank reversal probability. In the simulations we changed the number of attributes from 2 to 10. The results of our simulations are presented in Figure 8. In Figure 8. a) the efficiency of the original GRA method is presented. As it can be seen, in the worst cases the rank reversal probability can reach even 40%. Using *norm_2* and *norm_3* technique the rank reversal ratio is decreased. Figure 8. b) depicts the performance of *norm_2*, however the performance of *norm_3* technique is almost the same.

The impact of the number of network attributes is also observable. By increasing the number of network attributes used for decision making, the rank reversal probability increases. When there are more parameters that must be taken into account, the possibility that the removed network has more parameters, which are the highest or lowest attributes, will be higher.

The results confirm that by using absolute minimal and maximal values defined before the network selection, we can significantly decrease or even eliminate the possibility of the rank reversal phenomenon.

VI. Conclusion

The increase of multimedia applications over the Internet has placed new requirements on current video streaming solutions. High bandwidth video provision in mobile environment can be also available if the mobile terminal is equipped with more interfaces. With the effective utilization of the various links the quality of the video stream can be significantly increased. In this paper a content–aware interface selection scheme was presented, which provides efficient multipath delivery of MPEG video streams. In our solution a heap up buffer is applied to increase the efficiency of the packet distributions, in order to transfer the high priority data on the best links. In order to determinate the rank order of the links, we have investigated a modified GRA network ordering technique. Our aim was to reduce and eliminate ranking inconsistency, because it can potentially decrease the quality of the link by causing handovers whenever the list of the available networks changes. To evaluate our proposals, simulations were performed and the obtained results proved the efficiency of our multipath transmission scheme combined with modified GRA network ordering solution. Due to comprehensive modeling of video streams, the proposed low complexity solution provides an interesting and effective solution for video streaming in multipath infrastructures.

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