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Packet Dispersion Strategy Evaluation from the Perspective of Packet Loss Pattern and VoIP Quality

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Abstract. The appearance of burst packet losses and its devastating effect on Voice over IP (VoIP) service have imposed a requirement for the implementation of loss recovery mechanisms to address VoIP quality during periods when high packet loss is exhibited. Existing loss recovery mechanisms are dependent on end point capabilities, whereas Quality of service (QoS) routing protocols suffer from complexity and scalability issues. In this paper, we examine packet dispersion's ability to address burst losses and provide a computational model, which is verified using real network testing. A study has been carried out to investigate the effect of different packet dispersion strategies on burst losses, which clearly shows dispersion's qualitative superiority over single path routing. Furthermore, an analytical approach is proposed resulting in quality estimation obtained by individual strategies. Practical evaluation has shown that each strategy copes differently with various burst scenarios in order to maximize VoIP quality.

Keywords: burst loss, Markov model, packet dispersion, voice over IP, quality of service.

1. Introduction

Voice over IP (VoIP) in the past decade has become prevalent method of voice communication in the Internet whose high acceptance is primarily the result of its economic efficiency, flexibility and added features [1]. Packet loss is an extremely impairing factor, which is addressed by various mechanisms aiming to reduce negative effects on VoIP quality. Packet losses in the Internet usually appear in bursts making the quality impairment even more noticeable, consequently requiring the deployment of loss recovery techniques. These techniques are classified into two categories: sender-based and receiver-based. Sender-based techniques [2] tend to perform redundant transmission in order to improve robustness. Packet Loss Concealment (PLC) technique is a receiver-based mechanism with a purpose of hiding packet losses that occur on the network path.

Loss recovery mechanisms are generally deployed on end points alleviating network from loss recovery function. However, network's role in addressing packet losses is crucial for VoIP quality improvement perceived on end points. Packet dispersion is one of the network mechanisms able to increase resiliency to packet loss. It is often regarded as per-packet multi-path routing, although its objective is not load balancing, but dispersion of packets over paths with different quality of service (QoS) characteristics.

Such dispersion of packets contributes to the increase of distance between subsequent packet losses and shortening of loss bursts so that remaining packet losses in VoIP sessions may be more efficiently concealed by PLC algorithms. Packets are dispersed according to a particular dispersion strategy, which dictates the sequence of dispersion paths that subsequent packets take to destination. With the rising advent of multihoming, mainly relating to the mobility requirements [3, 4], packet dispersion presents a technique that can be tailored for future Internet intended to reduce packet loss effect on real-time multimedia and similar loss-sensitive services.

In this paper, we aim to provide detailed analytical and practical analysis of loss pattern and quality dependence on packet dispersion strategy. Analytical approach is taken to determine loss pattern in VoIP sessions stemming from individual dispersion strategies. Additionally, our focus was to put qualitative parameters into context with individual strategies, so that particular dispersion strategy yielding the highest VoIP quality may be selected based upon loss structure exhibited on dispersion paths. We achieve this by analytically determining parameter that accounts for burst losses, which is used as an input to assess VoIP quality according to the ITU-T E-model [5]. Moreover, we use real network and VoIP equipment to verify the accuracy of the analytical approach.

The rest of the paper is structured as follows. Section 2 contains background and related work. Packet loss modeling using 4-state Markov model along with a set of parameters pertinent to loss pattern characterization are shown in Section 3. Section 4 presents detailed computational analysis of loss and quality parameters associated with investigated dispersion strategies. Results and performance evaluation are provided in Section 5. Section 6 concludes the paper.

2. Background and Related Work

QoS techniques are commonly deployed in modern networks as they can provide quality guarantees in congestion scenarios through voice packet prioritization. However, packet losses may be caused by various events in networks not necessarily correlated to congestion, making QoS schemes useless in these cases. Suitable approach would be to perform routing policy modifications so that voice packets bypass the paths on which packet losses are detected.

Present tendency regarding network engineering and planning is to increase availability level by implementing high level of redundancy [6]. Such approach offers an alternative to conventional single path routing through the implementation of multi-path routing. Usage of packet dispersion is often avoided due to differing latencies between paths potentially impeding TCP performance [7, 8] as a result of packets arriving out of order. Conversely, real-time applications rely on Real-time Transport Protocol (RTP) to provide packet reordering function. With real-time services it is important that packets arrive on time to be passed in a constant stream to the upper layers. Consequently, high difference between path latency may cause additional packet losses. Packet dispersion from a load-balancing perspective is capable of achieving more accurate load-balancing in comparison to flow-level balancing and according to [9], dispersion can greatly improve packet queuing delay performance. Nevertheless, if dispersion paths have statistically significant difference in packet latency, VoIP quality may be hampered.

In the context of load-balancing Equal-Cost Multi-Path (ECMP) [10-13] routing is commonly used in networks as routing protocols calculate paths with equal cost. However, most of the existing routing protocols are not QoS-aware, which may lead to different characteristics of equal cost paths. Once path selection is complete, load distribution models are applied [11]: round-robin, hashing and adaptive. Load distribution models have not been investigated in the literature relating to the potential quality improvement of multimedia applications.

Research in [14-16] discusses path switching as a routing mechanism capable of providing better performance by dynamically switching from one path to another depending on the current path characteristics. Basic prerequisite for the implementation of path switching is the existence of path diversity [17-20] enabling the path switching strategy to elect a single appropriate path that would yield optimal performance in terms of QoS parameters. Main difference between these techniques is that packet dispersion uses multiple paths on per-packet basis, whereas path switching uses single path as long its QoS characteristics are satisfactory. Path switching and packet dispersion rely on the discovery of disjoint paths in order to provide superior performance. Algorithms for determination of disjoint paths are widely discussed in the literature [21].

Packet dispersion has also found its place in network security by lowering probability of packet interception when multiple paths are used. Research work presented in [22] proposes several algorithms that may, to some extent, improve VoIP security. Although not concerned with performance and quality issues, the objective of this approach tends to provide the required level of security without employing complex encryption.

The most notable contribution relating to the analysis of packet dispersion effect on VoIP quality may be found in [23]. The authors have shown that using round robin and random packet dispersion strategies distance between packet losses is increased when Bernoulli and burst packet losses are observed on the paths. However, the analysis did not provide the following: (1) the verification of the used approach; (2) dispersion strategy deficiencies to address particular loss scenarios; (3) analysis with only two dispersion paths has been considered. Moreover, in terms of packet loss, only loss distance is investigated. For complete and accurate analysis, inclusion of additional loss parameters needs to be made so that VoIP quality may be assessed.

To the best of our knowledge, previous work on packet dispersion is mainly based on load-balancing and security objective, whereas modification of loss pattern using different dispersion strategies has not been covered in detail. Bearing in mind the deficiencies of the work in [23], we extend mentioned analysis aiming to increase the accuracy with 4-state Markov loss model. We subsequently propose analytical scheme to quantify VoIP quality impairment caused by burst losses. Additionally, verification of the proposed analytical approach has been performed by comparing computed loss patterns with captured patterns using real network and VoIP traces.

The contribution of this paper may be summarized as follows: (1) accuracy improvement of loss pattern analysis with the introduction of 4-state Markov loss model; (2) proposal of analytics linking burst losses and quality assessment using E-model contingent on particular dispersion strategy; (3) verification of proposed analytical approach with captured traces from practical network testing; (4) comparison analysis in terms of loss and quality of existing (round robin and random) and additionally proposed (adaptive and redundant) dispersion strategies.

3. Packet Loss Pattern Analysis and Modeling

Packet loss is proven to be one of the main quality impairment factors stemming from measurements in service provider networks [24] and potentially limiting the perspective of VoIP from becoming widely deployed. Furthermore, it has been shown that packet losses mostly appear in bursts [25, 26], exhibiting strong long-term dependency. Burst losses decrease PLC's capability to conceal subsequent losses.

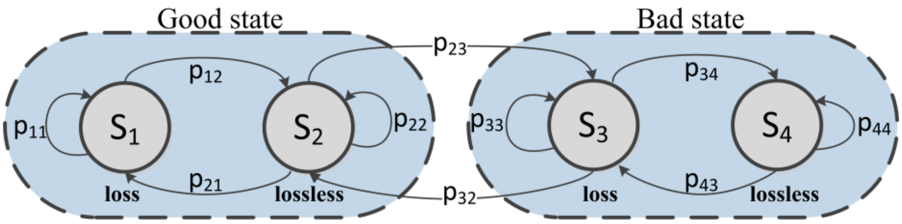

Fig. 1. Markov model with four states used to model VoIP packet losses.

Burst packet loss modeling takes the form of Markov chains, more precisely Gilbert [27] and Gilbert-Eliot [28] models, which are 2-state Markov models. Markov model with 4 states is proposed in [29] and presents a simplification of *n*-state Markov model. In this paper, burst packet losses are modeled according to the 4-state Markov model depicted in Fig. 1. It models long-term loss dependencies more accurately comparing to its 2-state counterparts [30], i.e. Gilbert and Gilbert-Eliot models. Recent analysis in [31] confirms that higher accuracy of loss modeling in VoIP may be achieved using 4-state model.

In 4-state Markov model, *good state* consists of S_1 and S_2 states, and *bad state* consists of S_3 and S_4 states. Each transition to S_1 and S_3 results in loss event, whereas transition to S_2 and S_4 results in lossless event. Accordingly, we provide analytical approach in calculating key loss parameters pertinent to the VoIP quality analysis.

3.1. Average and Noticeable Packet Loss

Transition matrix is provided in (1), whereas state probabilities for 4-state model are determined by solving the system of equations and are shown in (2).

$$T = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ p_{21} & p_{22} & p_{23} & 0 \\ 0 & p_{32} & p_{33} & p_{34} \\ 0 & 0 & p_{43} & p_{44} \end{bmatrix}, \tag{1}$$

$$\begin{cases} S_1 = \dfrac{p_{21} \cdot p_{32} \cdot p_{43}}{p_{21} \cdot p_{32} \cdot p_{43} + p_{12} \cdot p_{32} \cdot p_{43} + p_{12} \cdot p_{23} \cdot p_{43} + p_{12} \cdot p_{23} \cdot p_{34}}, \\ S_2 = \dfrac{p_{12} \cdot p_{32} \cdot p_{43}}{p_{12} \cdot p_{32} \cdot p_{43} + p_{21} \cdot p_{32} \cdot p_{43} + p_{12} \cdot p_{23} \cdot p_{34} + p_{12} \cdot p_{23} \cdot p_{43}}, \\ S_3 = \dfrac{p_{12} \cdot p_{23} \cdot p_{43}}{p_{12} \cdot p_{23} \cdot p_{43} + p_{12} \cdot p_{23} \cdot p_{34} + p_{32} \cdot p_{12} \cdot p_{43} + p_{21} \cdot p_{32} \cdot p_{43}}, \\ S_4 = \dfrac{p_{12} \cdot p_{23} \cdot p_{34}}{p_{12} \cdot p_{23} \cdot p_{34} + p_{12} \cdot p_{23} \cdot p_{43} + p_{12} \cdot p_{32} \cdot p_{43} + p_{21} \cdot p_{32} \cdot p_{43}}. \end{cases} \quad (2)$$

Aside from state probabilities, for accurate loss characterization on the path, it is important to determine Packet Loss Rate (PLR), loss probability in bad state (loss density), average burst length and Noticeable Loss Rate (NLR).

PLR is an average indicator of packet loss and as such is not able to capture burst patterns accurately. Therefore, the introduction of additional loss parameters is necessary to describe loss conditions. According to the 4-state Markov model, PLR is determined as a sum of loss state probabilities, i.e. $P_{loss}=S_1+S_3$.

NLR is loss metric that captures the loss proximity by counting “noticeable” losses. Every packet loss with distance, in terms of packet sequence number, less or equal than loss constraint δ from the previous packet loss is considered noticeable. Parameter δ refers to the quality of PLC scheme, thus its value is chosen accordingly. If PLC is able to conceal close losses, the loss constraint is lower. For the purpose of the NLR computational analysis in this paper, we use approach from [23] that marginally alters the formal NLR definition from [32]. Accordingly, NLR becomes the ratio of number of noticeable losses and total number of transmitted packets (instead of total number of lost packets). NLR is calculated as the difference of packet loss probability and probability that subsequent δ packets would not be lost. Accordingly, NLR is:

$$NLR^{(\delta)} = P[L(n)=1] - P[L(n)=1,\ L(n+1)=0,\dots,L(n+\delta)=0]\ , \quad (3)$$

where $L(n)$ is event function determining the loss event ($L(n)=1$) or lossless event ($L(n)=0$) of packet n.

To account for transitions to loss states, we subsequently define transition matrix T_{loss} containing transition probabilities that result in packet loss no matter which state model currently resides in:

$$T_{loss} = \begin{bmatrix} p_{11} & 0 & 0 & 0 \\ p_{21} & 0 & p_{23} & 0 \\ 0 & 0 & p_{33} & 0 \\ 0 & 0 & p_{43} & 0 \end{bmatrix}. \quad (4)$$

Appropriately, transition matrix T_{good} containing probabilities leading to lossless event can be determined as $T_{good} = T - T_{loss}$. State vector is defined as $S=\begin{bmatrix} S_1 & S_2 & S_3 & S_4 \end{bmatrix}$. Therefore, after one lost packet, probability that following δ subsequent packets would not be lost is $S \times T_{loss} \times (T_{good})^{\delta} \times I$, where I is $4x1$ matrix consisting of elements equal to 1. Considering NLR definition in (3), difference between PLR and $S \times T_{loss} \times (T_{good})^{\delta} \times I$ actually determines the probability of noticeable loss. Appropriately to the previous, NLR equals to:

$$NLR^{(\delta)} = P_{loss} - (S \times T_{loss} \times (T_{good})^{\delta} \times I), \tag{5}$$

3.2. Burst Loss Period

Burst period is determined by the time model spends in states S_3 and S_4, and it also depends on the probability of leaving the bad state, i.e. transitioning to state S_2 from state S_3. Mean burst length B expressed in the number of packets (actual time is determined by multiplying number of packets and codec packetization interval) equals:

$$B = \sum_{k=0}^{\infty} (E(S_3) + k \cdot (E(S_3) + E(S_4))) \cdot \frac{p_{32}}{p_{34} + p_{32}} \cdot (\frac{p_{34}}{p_{34} + p_{32}})^k = \frac{p_{34} + p_{43}}{p_{32} \cdot p_{43}}, \tag{6}$$

where k denotes a particular transition step to bad state, $E(S_3)=1/(p_{32}+p_{34})$ and $E(S_4)=1/p_{43}$ is an average time spent in states S_3 and S_4, respectively. For the previous calculation, $\frac{d}{dP}(\sum_{k=0}^{\infty} P^k) = \frac{1}{(1-P)^2}$ transformation is used. Loss probability during burst period, i.e. loss density, equals $P_{burst}=S_3/(S_3+S_4)$.

4. Packet Loss Pattern Analysis and Modeling

We assume the existence of end-to-end disjoint paths in order to achieve statistical independency of burst losses on paths. Dispersion strategy determines the sequence according to which packets are dispersed across paths, thus it is possible to obtain better VoIP quality. The selection of dispersion strategy should be based on burst losses exhibited on dispersion paths. In order to make the result of strategy selection deterministic, we have developed more accurate analytical approach incorporating 4-state Markov losses for each strategy in comparison to one in [23].

Using the proposed approach, it is possible to estimate loss pattern and select strategy that yields targeted performance. It can also be used to identify potential caveats of proposed strategies relating to the existing loss patterns. Furthermore, for each strategy, we propose analytical scheme to determine *BurstR* parameter, a part of ITU-T's E-Model [5], which accounts for quality degradation due to existence of burst losses.

4.1. Periodic Dispersion Strategy

Periodic dispersion strategy assumes the existence of periodic function $Q(i)$ with period K that dictates packet dispersion sequence over N paths. Consequently, $Q(i) \in \{1,2,...,k,..,N\}$ decides which path the specific packet i takes among N paths (p_1, p_2, ... ,p_k,..., p_N). Bearing in mind NLR and probability difference in (3), given the loss constraint δ, noticeable losses are avoided if packet i is lost on path p_k, while no losses occur for subsequent δ packets sent over this path conforming to $Q(i+l)=k$, $l \in \{1,...,\delta\}$. For packets complying to $Q(i+l)\neq k$, it is irrelevant if loss or lossless event occurs on p_k. Accordingly, we denote this "irrelevant" event as $L(i)=2$. Simultaneously, for other dispersion paths, $p_r \neq p_k$ ($r \in \{1,...,N\}$ and $r\neq k$), no losses should occur for subsequent δ packets for which $Q(i+l)=r$, whereas event is irrelevant for $Q(i+l)\neq r$. In order to account for discussed events, a new transition matrix $T^{(k)}_{good,k}$ for path k is introduced determined as

$$T^{(k)}_{good\,k}(i)=\begin{cases} T_{good\,k}\ ,for\ path\ p_k\ according\ to\ Q(i)=k \\ T_k\ ,otherwise \end{cases}, \tag{7}$$

where $T_{good,k}$ is transition matrix T_{good} for path p_k meant to account for packets complying to $Q(i)=k$, wheras T_k is transition matrix complying to $Q(i)\neq k$.

Probability of noticeable loss $P_k[NL^\delta]$ on path p_k is determined as a difference between loss probability of packet i on path p_k and probability that it is not a noticeable loss stemming from previous discussion. Without diminishing generality of periodic function, we further investigate round robin strategy. We assume that function $Q(i)$ corresponds to round robin policy for $k=1$, $N=2$ and $K=2$. Further assuming that lost packet i occurs on path p_1, (loss probability is $P_1[L_{Q(i)=1}(i)=1]$), probability that following δ packets are not noticeable loss on path p_k is joint probability $P_1[L_{Q(i)=1}(i)=1,\ L_{Q(i+1)=2}(i+1)=2,\dots,L_{Q(i+\delta)=1}(i+\delta)=0]$. This indicates that following packets ($i+1$, $i+2$, ..., $i+\delta$) on path p_1 are either not lost when $Q(i)=1$ (i.e. $L_{Q(i+\delta)=1}(i+\delta)=0$) or they are "irrelevant" (i.e. $L_{Q(i+1)=2}(i+1)=2$) when $Q(i)\neq 1$. Additionally, similar approach applies for the other paths that did not have initial packet loss. The appropriate probability that noticeable loss does not occur on paths different than p_1 is $\prod_{\substack{r=1 \\ r\neq k}}^{N=2} P_r[L_{Q(i)=1}(i)=2,\ L_{Q(i+1)=2}(i+1)=0,..,L_{Q(i+\delta)=1}(i+\delta)=2])$. Therefore, noticeable loss $P_k[NL^\delta]$ when initial packet loss is on path p_k, for $k=1$ equals:

$$\begin{aligned} P_k[NL^\delta] = {} & P_k[L_{Q(i)=1}(i)=1]-(P_k[L_{Q(i)=1}(i)=1,\ L_{Q(i+1)=2}(i+1)=2,\dots,L_{Q(i+\delta)=1}(i+\delta)=0]\cdot \\ & \cdot\prod_{\substack{r=1 \\ r\neq k}}^{N=2} P_r[L_{Q(i)=1}(i)=2,\ L_{Q(i+1)=2}(i+1)=0,..,L_{Q(i+\delta)=1}(i+\delta)=2])\ . \end{aligned} \tag{8}$$

Without the loss of generality, by putting analytical expression from (8) in matrix form, probability that packet i is a noticeable loss equals:

$$P[NL^{\delta}] = P_{loss\,k} - (S_k \times T_{loss\,k} \times (\prod_{l=1}^{\delta} T^{(k)}_{good\,k}(i+l)) \times I) \cdot \prod_{\substack{r=1 \\ r \neq k}}^{N} (S_r \times (\prod_{l=1}^{\delta} T^{(r)}_{good\,r}(i+l)) \times I) \quad , \tag{9}$$

where $P_{loss,k}$, $T_{loss,k}$ and S_k are PLR, matrix containing transition probabilities to loss states and state vector for path p_k, respectively. Equation (9) addresses cases when initial packet loss is on p_k. Since all paths have equal probabilities to have initial packet loss during period K, NLR is determined for all dispersion paths:

$$NLR^{(\delta)} = \frac{1}{K}\sum_{i=1}^{K}(P_{loss,Q(i)} - (S_{Q(i)} \times T_{loss,\,Q(i)} \times (\prod_{l=1}^{\delta} T_{good,\,Q(i)}(i+l) \times I)) \cdot \prod_{\substack{r=1 \\ r \neq Q(i)}}^{N} (S_r \times (\prod_{l=1}^{\delta} T^{(r)}_{good,\,r}(i+l)) \times I))) \cdot \tag{10}$$

BurstR [5] parameter is essential for examining the burst effect on quality evaluated using E-model and according to its definition is equal to:

$$BurstR = \frac{P_{loss}}{p_{g-b}} \, , \tag{11}$$

where p_{g-b} is transition probability from lossless states (S_2 and S_4) to loss states (S_1 and S_3). In order to determine p_{b-g}, we first need to determine the packet loss probability P_{g-b} stemming from the transition from lossless states, which is equal to

$$P_{g-b} = \frac{1}{K}\sum_{i=1}^{K} S_{good,Q(i)} \times T_{g-b,Q(i)} \times I \, , \tag{12}$$

where $S_{good,Q(i)}$ is state vector containing lossless states, i.e. S_2 and S_4, $T_{g\text{-}b,\,Q(i)}$ is matrix containing only transition probabilities from S_2 and S_4 to S_1 and S_3. Therefore, p_{g-b} is

$$p_{g-b} = \frac{P_{g-b}}{1 - P_{loss}} \, . \tag{13}$$

4.2. Random Dispersion Strategy

Random strategy assumes that each dispersion path has associated dispersing probability φ over a given path for which equality $\sum_{i=1}^{N} \varphi_i = 1$ applies. NLR for random strategy is determined using “equivalent path” approach. We consider the equivalent path as a path that exhibits loss pattern properties of N individual paths over which random dispersion strategy is applied. Consequently, both of transition matrix T_{equi} and state vector S_{equi} consist of all possible combinations of transition probabilities and states associated with N dispersion paths. To account for all transitions and all states on equivalent path formed from N dispersion paths, state vector S_{equi} and transition matrix T_{equi} have dimensions *1xN* and *NxN*, respectively. Considering previously stated, Kronecker product is applicable in terms of generating state vector $S_{equi} = S_1 \otimes S_2 \otimes ... \otimes S_N$ and transition matrix $T_{equi} = T_1 \otimes T_2 \otimes ... \otimes T_N$ for “equivalent path.

We further introduce a loss indicator matrix A_{loss} parameter to account for dispersing probability φ on equivalent path. Loss indicator matrix is a $4^N x 4^N$ matrix containing on the main diagonal loss probability for all combination of states on used dispersion paths. Example of A_{loss} for 2 paths (with probabilities φ_1 and φ_2) is given in the following

$$A_{loss} = \begin{bmatrix}
\varphi_1+\varphi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \varphi_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \varphi_1+\varphi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_1+\varphi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_1+\varphi_2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi_2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (14)$$

Separate elements on the main diagonal of A_{loss} matrix are determined as following. For the combination of loss states on both paths loss probability is $\varphi_1 + \varphi_2$, for combination of lossless and loss event loss probability is φ_1 or φ_2 depending on which path is found in loss state, whereas combination of two lossless state yields loss probability of 0. Appropriately, lossless indicator matrix is $A_{no\text{-}loss} = I_d - A_{loss}$, where I_d is identity matrix. NLR is then determined for this equivalent path, similar to (5), as:

$$NLR^{(\delta)} = P_{loss,\,equi} - (S_{equi} \times (T_{equi} \times A_{loss}) \times (T_{equi} \times A_{no-loss})^{\delta}) \times I\ ), \quad (15)$$

where I is $4^N x1$ matrix containing all 1’s and $P_{loss,\,equi} = \sum_{i=1}^{N} \varphi_i \cdot P_{loss,i}$ is PLR on equivalent path.

For *BurstR* parameter we calculate $P_{g\text{-}b}$ according to random strategy, whereas (11) and (13) also apply here. On the equivalent path good states are formed from the combination of all good states on *N* paths. Probability $P_{g\text{-}b}$ equals

$$P_{g-b} = S_{good,equi} \times (T_{g\text{-}b,equi} \times A_{g-b,equi}) \times I\ , \quad (16)$$

where $S_{good,equi} = S_{good,1} \otimes S_{good,2} \otimes .... \otimes S_{good,N}$, $T_{g-b,equi} = T_{g-b,1} \otimes T_{g-b,2} \otimes .... \otimes T_{g-b,N}$, whereas $A_{g\text{-}b,equi}$ is burst indicator matrix containing elements representing transitions from lossless to loss states on the equivalent path, whereas remaining elements are 0. For equivalent path to be found in lossless state, each path forming equivalent path must be in S_2 or S_4 state. To be found in loss state, at least one path involved in equivalent path must be in S_1 or S_3. Therefore, non-zero elements in $A_{g\text{-}b,equi}$ assume positions in matrix signifying transitions according to stated rules. Each non-zero element is equal to the sum of dispersing probabilities φ_i, if and only if, path P_i transitions from lossless to loss state.

Adaptive Random Dispersion Strategy. Random dispersion strategy offers a degree of flexibility reflected in the modification of path probabilities φ. We propose that path probabilities φ are calculated depending on PLR on dispersion paths, thus packets are more probable to be sent over paths with lower PLR. Accordingly, probability φ_k is equal to:

$$\varphi_k = \frac{1}{N\text{-}1} \cdot \frac{\sum_{\substack{i=1 \\ i \neq k}}^{N} P_{loss,i}}{\sum_{i=1}^{N} P_{loss,i}} . \quad (17)$$

Adaptive strategy relies on packet loss monitoring and periodic adjusting of φ parameters, consequently making φ time variable parameter. Packet dispersion dynamic activation mechanism [33] combined with packet loss measurement is suitable for concurrent use with this adaptive strategy. Such approach is very useful when appearance of burst loss occurs on a temporary basis on dispersion paths, thus packet dispersion is activated, if necessary, to achieve better performance.

Inherent complexity issues with implementation of adaptive strategy may arise from the requirement for tracking loss characteristics on multiple paths designated for dispersion. Also, implementation of dynamic packet dispersion mechanism may impose additional complexity on dispersion routers in networks.

4.3. Redundant Dispersion Strategy

Redundant dispersion assumes that each voice packet is replicated and sent concurrently over each dispersion path. This leads to increase in bandwidth requirement proportionally to the number of used dispersion paths. Consequently, packet loss robustness is significantly increased as probability of single packet reaching the destination is increased. Additionally, the higher the losses on the paths, the higher should be the number of used dispersion paths. Analysis of redundant dispersion effect on VoIP quality is presented in [34]. However, the effect of this strategy on loss pattern has not been examined.

Packet loss during redundant dispersion over N separate paths occurs when each path simultaneously transitions to loss state. Using the “equivalent path” approach as with random dispersion strategy, available dispersion paths form equivalent path with S_{equi} *and* T_{equi} parameters. Since redundant strategy sends a single packet over N paths without the requirement to implement specific order in dispersing packets, NLR is equal to:

$$NLR^{(\delta)} = S_{equi} \times (T_{loss,1} \otimes T_{loss,2} \otimes \ldots \otimes T_{loss,N}) \times I - \\ - S_{equi} \times [(T_{loss,1} \otimes T_{loss,2} \otimes \ldots T_{loss,N}) \times (T_{good,1} \otimes T_{good,2} \otimes \ldots \otimes T_{good,N})^{\delta}] \times I . \tag{18}$$

Analogous approach is used for *BurstR* parameter. Since state vector $S_{good,equi}$ contains lossless states and transition matrix $T_{g\text{-}b,equi}$ is Kronecker product of all $T_{g\text{-}b}$ matrices associated with dispersion paths, probability $P_{g\text{-}b}$ is determined as

$$P_{g-b} = S_{good,equi} \times T_{g\text{-}b,equi} \times I \ , \tag{19}$$

where I is $4^N x1$.

5. Results and Discussion

Previously analyzed dispersion strategies are evaluated from packet loss perspective through the process of practical tests. Tests have been conducted on real network equipment making over 250 VoIP calls of various time lengths and modeling wide range of burst losses on network paths. The effect of separate dispersion strategies and number of dispersion paths on loss pattern and VoIP quality is observed. Furthermore, verification of proposed analytics is compared with practical results.

Dispersion router is a high performance Linux machine implementing analyzed strategies. Dispersion strategies are accomplished through the implementation of per-packet routing policies on dispersion router, providing flexibility to create custom dispersion strategies over available network paths. VoIP calls have been made by using Cisco VoIP phones[1], which are registered to *Cisco 3725 Multiservice Access Router* with IP telephony features. This setup enables the deployment of VoIP service and call signaling between registered VoIP phones. Once established, call session is using G.711 codec, a widely used codec in VoIP deployments. Use of a single codec does not diminish the accuracy of our study as packet dispersion strategies affect only packet loss pattern regardless of deployed codec. VoIP quality is based on E-model and is determined by using resulting loss pattern and additional E-model parameters (e.g. specifying codec's robustness to packet loss) that apply to specific codecs. Therefore, the results presented in this evaluation in terms of loss pattern apply to other codec types as well.

Recent modification of NETEM [35] module integrated on dispersion router is used for introducing 4-state Markov losses and latency on separate dispersion paths allowing to test various network conditions, thus creating the opportunity to observe immediate effect on VoIP quality. Proposed analytical approach and loss pattern analysis from captured VoIP traces have been implemented using MATLAB. High level overview of testbed setup is depicted in Fig. 2.

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[1] Cisco IP phones *SPA502G* and softphones *Cisco IP Communicator* have been used in the testbed. These phones are equipped with adaptive jitter buffer, which minimizes the impact of jitter effects on VoIP quality.

Previous discussion has shown that single loss parameter is not enough for comprehension of loss impact on VoIP quality. Therefore, the analysis consists of several parts: (1) verification of loss distance analytics; (2) practical comparison of strategies in terms of separating packet losses, i.e. NLR analysis; (3) quality comparison of strategies according to the E-model. It is important to highlight that random strategy assumes equal dispersing probability φ for all dispersion paths.

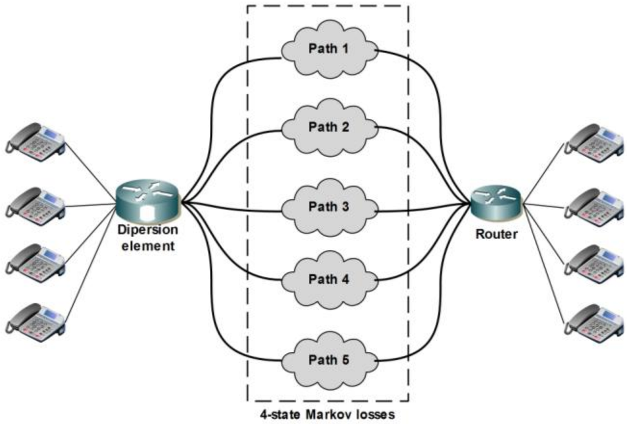

Fig. 2. Packet dispersion testbed.

5.1. Analytical Approach Accuracy Verification

In order to examine the suitability and accuracy of analytical approach for different strategies, we compare NLR parameters stemming from proposed approach and practical testing.

Relative error ε is examined as a measure of accuracy, which is determined as follows

$$\varepsilon = \left| 1 - \frac{\frac{1}{F} \cdot \sum_{i=1}^{F} NLR_{msrm,i}}{NLR_{analyt}} \right| , \tag{20}$$

where NLR_{msrm} and NLR_{analyt} denote measured and calculated NLR values, respectively, whereas F denotes the number of conducted measurements in order to obtain mean value of measured NLR. For the purpose of accuracy analysis, we performed five NLR measurements, i.e. $F=5$.

We assume there are two dispersion paths. The first path has $PLR=5\%$ and $B=30$ *packets*, whereas loss characteristics is varied in wide range on the second path. Comparison of analytical accuracy is depicted in Fig. 3 for observed strategies. For each of the strategies, relative error is less than 6% yielding satisfying accuracy. However, there are notable differences among strategies in terms of accuracy.

Round robin has the highest ε as a result of used approach that has shown that problem is solvable in N dimensional space simultaneously taking its toll on accuracy. The "equivalent path" approach in solving random and adaptive random strategies requires the consideration in 4^N dimensional space resulting in exponential increase in complexity with the increase of number of dispersion paths. However, according to the results, benefit of using more complex analytics leads to higher accuracy. On the other hand, highest accuracy of redundant strategy is inherent to its simple operation, i.e. redundant dispersion over available dispersion paths. Such implementation in terms of analytics is brought down to multiplication of separate paths' state and transition probabilities via Kronecker product, which yields relative error no higher than 2%. Redundant strategy does not require involvement of analytically complex parameters to account for intricate dispersion policies, as it is the case with aforementioned counterparts, i.e. round robin and random dispersion strategies.

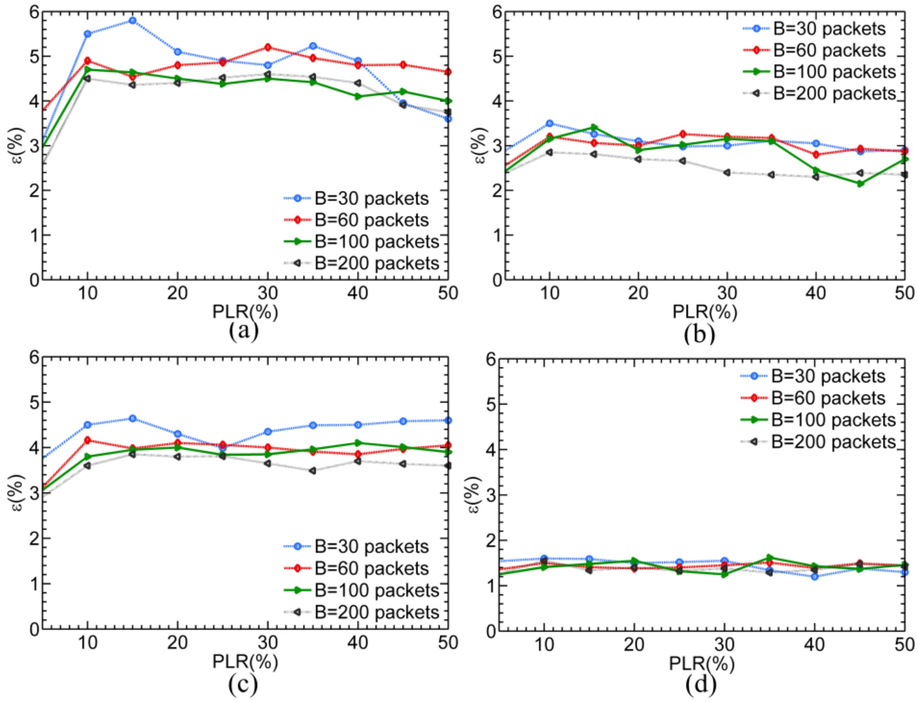

Fig. 3. Computational accuracy in terms of relative error ε: (a) Round robin; (b) Random; (c) Adaptive; (e) Redundant strategy.

It is important to highlight that results depicted in Fig. 3 demonstrate that analytical approach may be used with high confidence to estimate dispersion effect, whereas path characteristics have very limited influence on the accuracy of analytical approach.

5.2. Loss Distance Analysis

NLR is calculated from captured VoIP traces given the various numbers of paths and used dispersion strategies. We adopt $\delta=3$, accounting for low-quality PLC algorithms. Higher δ values bear no significance due to concealment abilities by PLCs. Assuming the existence of two paths with different PLR, comparison of round robin, random and adaptive strategy in terms of NLR is depicted in Fig. 4. The absence of packet dispersion is also compared to round robin and random strategies.

It is clear that use of any packet dispersion strategy provides superior results in terms of NLR in comparison to the absence of packet dispersion (Fig. 4(a) and Fig. 4(b)). Comparison of round robin, random and adaptive random strategies is depicted in Fig. 4(c)-(e). Random dispersion superiority over round robin is the result of dispersion dependence on paths' dispersing probability allowing subsequent packets to traverse the same path, thus avoiding paths with longer bursts. Clearly, adaptive strategy has better performance in comparison to round robin and random. Adaptive strategy is able to achieve up to 85% better NLR results than random strategy.

Since redundant strategy can easily handle worst case scenarios, we investigate the NLR dependence for two paths with equal PLR observing wider range of loss constraint δ. Consideration of wider range of δ demonstrates redundant strategy's effect on implemented PLC schemes. Significant gain (Fig. 4(f)) is achieved through redundant strategy, attaining 10-90% lower NLR comparing to the absence of dispersion depending on the PLR on dispersion paths.

It is important to highlight from Fig. 4(a)-(e) that little or no NLR gain is achieved when similar loss pattern is present on both paths. This identifies important limitation on the use of packet dispersion as these cases may lead to even worse loss pattern prompting us to investigate this scenario more closely. We subsequently observe a scenario to analyze dispersion's behavior under similar loss pattern. Consequently, under these circumstances adaptive becomes random strategy as path probabilities are equal for all paths according to (17). In Fig. 5 NLR results are depicted when up to 5 paths with same PLR are used with round robin, random and redundant strategies.

Provided results indicate that with round robin and random strategies no significant NLR improvements is achieved. Moreover, round robin may even express worse NLR results. Consequently, it is better to avoid round robin in these cases. Random strategy shows slight improvement in terms of loss distance with high PLR (Fig. 5(b)) as opposite to low PLR when no improvement is achieved. It is important to note that increase in path number does not lead to any increase in loss distance. Redundant strategy, however, shows NLR improvement directly related to the number of paths (Fig. 5(c)). This is the result of packet replication over dispersion paths and consequent reduction of resulting PLR. Based on the targeted quality for redundant strategy, improvement of loss distance is achieved by including additional dispersion paths.

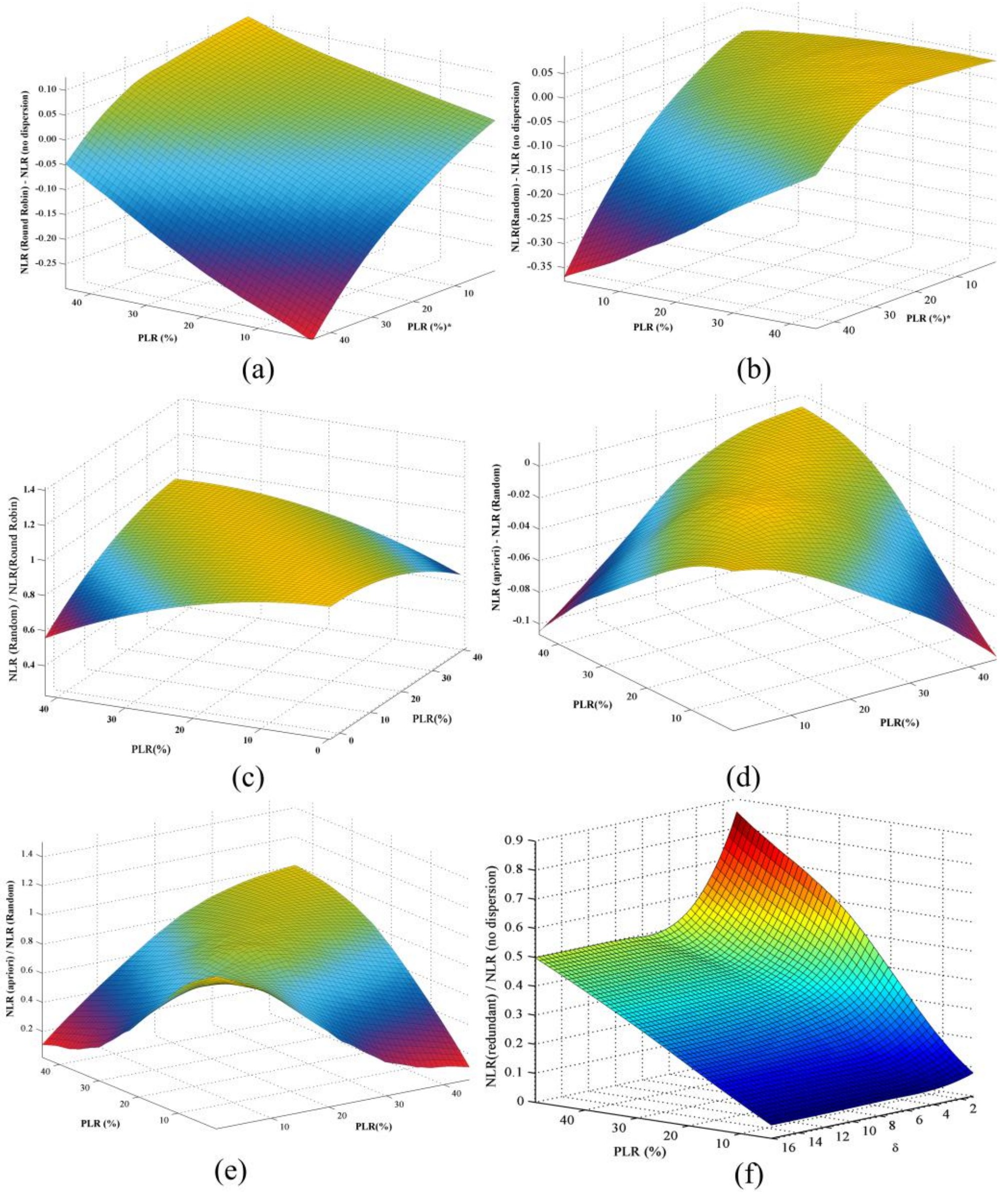

Fig. 4. NLR comparison: (a) Round robin and no-dispersion difference; (b) Random and no-dispersion difference; (c) Random and round robin ratio; (d) Adaptive and random difference; (e) Adaptive and random ratio; (f) Redundant strategy for different δ.

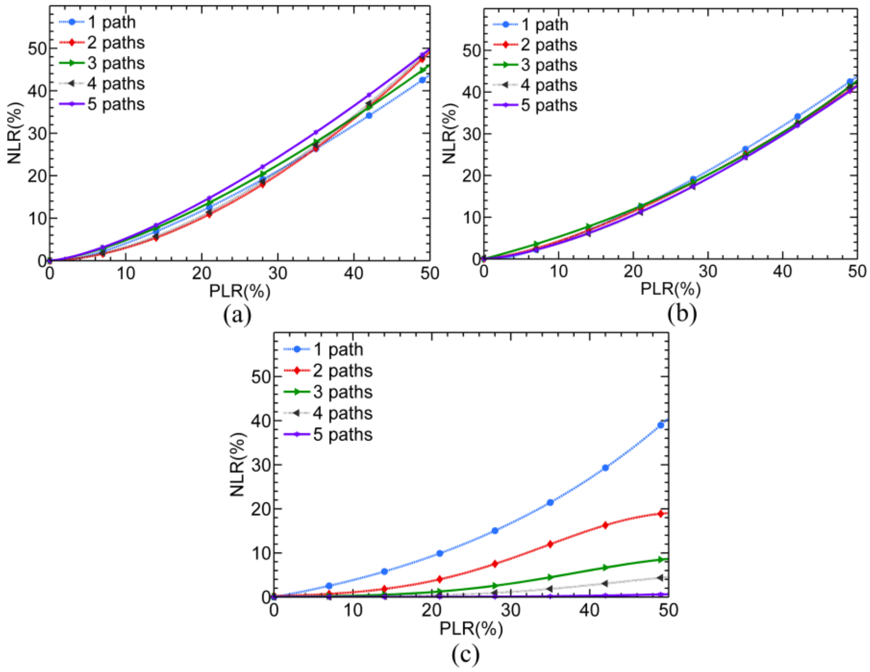

Fig. 5. Strategy comparison with respect to NLR when all paths have same burst characteristics (*B=100 packets*): (a) Round Robin; (b) Random; (c) Redundant.

5.3. VoIP Quality Analysis

Qualitative analysis encompasses individual strategies and their effect on VoIP quality according to the E-model. Since previous analysis includes loss parameters, which are considered technical parameters, it is reasonable to choose objective quality assessment method such as E-model where these parameters are used as an input. The output of an E-model is expressed as R factor (ranging values 1-100) and is converted into Mean Opinion Score (MOS), which designates perceived voice quality, ranking the quality as number in the range of 1 (low quality) to 5 (high quality). Table 1 shows the relation between R factor and MOS. This mapping is calculated using the following equation [36]:

$$\mathrm{MOS} = \begin{cases} 1, & \textit{for } R < 0 \\ 1 + 0.035 \cdot \mathrm{R} + \mathrm{R} \cdot (\mathrm{R} - 60) \cdot (100 - \mathrm{R}) \cdot 7 \cdot 10^{-6}, & \textit{for } 0 \le R \le 100 \\ 4.5, & \textit{for } R > 100 \end{cases} \quad (20)$$

Discussion regarding VoIP quality almost always refers to QoS in terms of latency, jitter and packet loss rate. However, the study presented in [37] has shown that in the presence of packet loss (as is the case with our packet dispersion evaluation), impairment as a result of delay and jitter is almost imperceptible, providing strong vindication to use packet dispersion as it mitigates the effect of packet loss at the expense of delay and jitter. Furthermore, it was shown in [38] that one-way latency below 177 ms does not impair conversation allowing it to be carried out without significant degradation in listening quality. Above this value, latency parameter starts to have impact on perceived quality. In terms of jitter, the majority of VoIP endpoints are equipped with jitter buffer that is able to cope with high variations in latency enabling smooth voice packet flow. The effect of de-jittering buffer adds to the packet latency, so jitter parameter may affect quality in case of very high one-way delays.

Table 1. R factor and MOS mapping

R-Value	*Satisfaction levels*	*MOS*
90-100	Very satisfied	4.3+
80-90	Satisfied	4.0-4.3
70-80	Some users dissatisfied	3.6-4.0
60-70	Many users dissatisfied	3.1-3.6
50-60	Nearly all users dissatisfied	2.6-3.1
0-50	Not recommended	1.0-2.6

For the purpose of this assessment, we adopt default values of E-model parameters according to [5], whereas dispersion paths have packet latency between 60 ms and 80 ms. This range in latency values, according to the previously stated, does not carry notable impairment on MOS value.

Following scenario assumes two paths with significantly differing loss patterns aimed to show a realistic scenario in which voice packets are dispersed over two dispersion paths conforming to the given dispersion strategy. According to the captured VoIP streams in the testbed, we are able to estimate the loss pattern resulting from used dispersion strategies. Estimation of 4-state Markov model parameters from captured VoIP traces is performed using an approach presented in [39]. According to this methodology, parameters associated with 4-state Markov model are determined, whereas lost packet is considered to be a part of burst if distance from previous loss is less or equal than g_{min} packets. Parameter g_{min} is used to identify burst losses, i.e. transitions to bad states and accordingly, to determine transition probabilities which we covered earlier. For the purpose of VoIP, recommended g_{min} value in [39] corresponding to good quality is $g_{min}=16$ packets and allows clear distinguishing of good and bad states in loss pattern. Higher g_{min} values would correspond to services that are more loss sensitive, e.g. for video services. For such services more appropriate g_{min} value would be 64 or 128, which would result in higher number of loss bursts in comparison to $g_{min}=16$.

For the quality assessment, we investigate the impact various dispersion strategies have on VoIP quality when two dispersion paths are available. Loss pattern parameters in Table 2 are acquired by capturing real VoIP traces on the testbed. Loss pattern specifications for *Path 1* and *Path 2* are shown in terms of packet loss probability P_{loss}, number of burst occurrences (as dictated by g_{min} parameter), mean burst length B and P_{burst}, which denotes loss probability during burst state. Once the required parameters are known, *BurstR* is calculated using proposed analytics and a comparison of VoIP quality is provided for all strategies in terms of MOS. Same methodology is used to identify loss pattern when round robin, random, adaptive random and redundant dispersion strategy are applied over *Path 1* and *Path 2* as dispersion paths.

Quality comparison is depicted in Fig. 6 and is presented for conventional single path routing (voice packets are sent over *Path 1*), round robin, random, adaptive random and redundant strategies. Based on the loss pattern specified in Table 2, round robin and random strategies have similar quality score (random offers slightly better quality), whereas adaptive and redundant are significantly better than previous two. Good quality score of adaptive strategy is directly related to the higher PLR difference of two paths. Redundant strategy is better in terms of quality than adaptive by almost completely eliminating bursts and leaving remaining voice gaps to be concealed by PLC. Comparison between adaptive random and redundant strategy shows the difference in MOS of 0.21, which is the effect of MOS and packet loss relation, since for lower P_{loss} values (less than 5%) MOS slowly converges toward excellent quality [40]. Notably, every examined dispersion strategy yields significantly better results in comparison to single path routing as a consequence of high loss difference between dispersion paths and high burst losses expressed on *Path 1*.

Table 2. Path specification for quality assessment

Path / Dispersion strategy	P_{loss} *(%)*	*Burst occurrences*	*B (packets)*	P_{burst} *(%)*
Path 1 (Single path routing)	13.60	162	41.85	10.25
Path 2	1.38	13	19.03	2.56
Round robin	7.43	154	27.68	7.02
Random	6.71	140	26.82	6.52
Adaptive random	2.61	46	22.89	1.85
Redundant	0.15	11	10.95	0.08

For low loss scenarios, optimal choice would be to use proposed adaptive random strategy or even round robin and random, which provides considerably better quality performance in comparison to the absence of packet dispersion. High loss scenarios on several paths require the use of redundant strategies entailing higher bandwidth requirements. Scenario involving significant loss difference between paths is suitable for adaptive strategy, for which implementation complexity issues should be considered. Based on the aimed quality level and available dispersion paths, dispersion strategy selection should be performed as a trade-off between complexity, bandwidth and strategy's susceptibility to particular loss scenarios (e.g. similar loss pattern on dispersion paths).

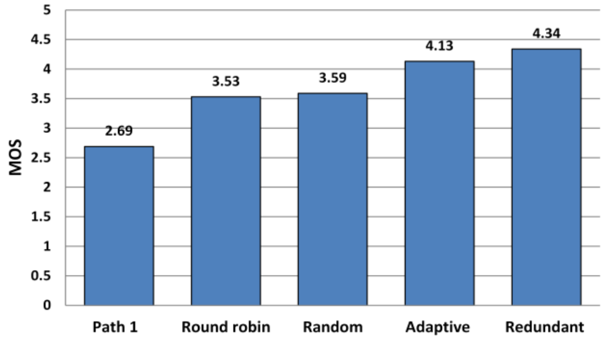

Fig. 6. Quality comparison of packet dispersion strategies.

6. Conclusion and Future Work

Packet dispersion presents a promising technique capable of using existing path redundancy and routing policies with minimal efforts in implementation process without employing complex and large-scale QoS-aware solutions. Provided analysis has shown that obtained quality generally depends on applied strategies and burst loss characteristics on network paths. Detailed dispersion strategy analysis provided in this paper distinguishes key differences between strategies, as well as their caveats and potential use in different loss scenarios. Furthermore, verification has demonstrated that high accuracy exists between provided computational approach and measured loss parameters.

Performed analysis and testing pertaining packet dispersion strategies produces strong foundation in developing QoS-adaptive multipath routing protocols. Our future work focuses on defining disjoint path routing algorithms able to take into account multiple QoS parameters and determine disjoint paths capable to be used for previously evaluated dispersion strategies aiming to maximize QoS performance.

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