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Performance Evaluation of Bandwidth Adaptation over DVB Satellite Channels

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Abstract— **This paper shows a detailed performance evaluation of the bandwidth allocation algorithm presented in [1] by the same research group and briefly reminded here. Telecommunications networks are composed of functional layers acting in cascade. The mentioned algorithm adapts the bandwidth to be allocated to a buffer which conveys heterogeneous traffic in a layer-in-cascade functional model, is based only on measures and does not use closed-form expressions, a-priori information about traffic statistical properties, and assumptions about buffer dimension. It is called RCBC (Reference Chaser Bandwidth Control) in [1]. The performance evaluation presented here is aimed at getting a general validation by testing RCBC over multiple DVB-based satellite scenarios and by analyzing the robustness of the algorithm against parameter variations. The performance evaluation is carried out through multiple performance metrics and, in consequence, the results are interpreted through MADM (Multi Attribute Decisions Making) theory, which is appropriate to take decisions in presence of multiple performance indicators.**

Index Terms—**Telecommunications Networks, Satellite Communications, Dynamic Bandwidth Allocation, Performance Evaluation.**

I. INTRODUCTION

THE vertical interaction between layers in cascade is defined as “Vertical QoS Mapping” [2]. Due to the problems that information meets when it passes through adjacent layers, bandwidth enlargement is necessary but the precise amount of necessary bandwidth is hard to compute. This is the aim of the RCBC algorithm presented in [1]. Precise references to the state-of-the-art and practical applications within the SES (Satellite Earth Stations) ETSI (European Telecommunications Standards Institute), BSM (Broadband Satellite Multimedia) working group (see references from [3] to [8]) are reported in [1].

The algorithm is briefly revised here to allow the reader to understand the content of this paper without accessing the paper in [1] but, actually, the novelty of the paper is represented only by the complete RCBC performance evaluation. For this, many RCBC details, not essential for the performance evaluation are not reported here.

Many performance indicators are used to evaluate the algorithm. For this motivation the paper shows and comments the results through the Multi-Attribute Decisions Making (MADM) theory [9], which is suited to make evaluations when there are multiple performance indicators.

The remainder of the paper is organized as follows. Section II summarizes the application framework and the RCBC bandwidth adaptation scheme, Section III briefly describes other bandwidth allocation techniques used in the performance evaluation for comparison. Section IV shows the simulation results. Section V contains the conclusions..

II. RCBC BANDWIDTH ADAPTATION SCHEME

Each protocol layer is modeled through blocks of queues acting in cascade. There are three problems arising from the action of layers in cascade [1]. 1) Change of information unit, which implies additional informational (overhead) and bandwidth update, when information passes from upper to lower layer. 2) Aggregation of heterogeneous traffic. 3) Fading effect. The three problems presented above can be seen jointly. The overall cascade-of-queues model may be described through N buffers at upper layer (identified as Technology Independent (TI) in [1] to mimic the definitions reported in references from [2] to [8]) identified through the index $i = 1,...,N$ and one at lower layer (identified as Technology Dependent (TD) in [1]) to simplify the presentation. The bandwidth assigned to each buffer so to provide a given quality of service to the flows entering the buffer is identified as $R_{id}^{TI}(t)$ at upper layer (where $id = h,i,j$ identifies the buffer and as R^{TD} at lower layer. From the mathematical viewpoint, the fading effect over satellite is modeled as a reduction of the bandwidth actually “seen” by the lower layer buffer. The reduction is represented by a stochastic process $\phi(t)$. At time t, the “real” service rate $R_{real}^{TD}(t)$ (available for data transfer) is $R_{real}^{TD}(t) = R^{TD}(t) \cdot \phi(t)$, $\phi(t) \in [0,1]$.

RCBC is aimed at dimensioning the bandwidth at lower layer so that the service is transparently guaranteed to the upper layer.

Time variable t_k identifies the reallocation instants. Index k is a progressive integer. The bandwidth is decided at the instants $[..., t_{k-3}, t_{k-2}, t_{k-1}, t_k]$. There are N traffic classes, one for each buffer. $a_i(t)$ is the input rate process of the $i-th$ traffic class and $a(t)$ the aggregate process of all $a_i(t)$, $i = 1,...,N$.

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$R_i^{loss}\left(R^{TD}(t),t\right)$ is the loss rate process of the $i-th$ traffic class in [packet/s]. $R_i^{delay}\left(R^{TD}(t),t\right)$ is the rate of the packets which arrive with a delay over a given threshold d_{thr} [s]. $Loss_{i,thr}(t)$ is a probability that represents the performance threshold of the loss rate for class i. $Delay_{i,thr}(t)$ is a probability that represents the performance threshold of the delay rate for class i. $R_{i,thr}^{loss}(t)=a_i(t)\cdot Loss_{i,thr}(t)$ is the loss rate process that can be tolerated (the loss rate threshold) of the $i-th$ traffic class [packet/s]. $R_{i,thr}^{delay}(t)=a_i(t)\cdot Delay_{i,thr}(t)$ is the delayed packet rate process that can be tolerated (the delayed packet rate threshold) of the $i-th$ traffic class [packet/s]. The average values of $R_i^{loss}\left(R^{TD}(t),t\right)$, $R_i^{delay}\left(R^{TD}(t),t\right)$, $R_{i,thr}^{loss}(t)$ and $R_{i,thr}^{delay}(t)$ are respectively: $\overline{R}_i^{loss}$, $\overline{R}_i^{delay}$, $\overline{R}_{i,thr}^{loss}$, $\overline{R}_{i,thr}^{delay}$, formally defined in [1].

The aim is to provide the minimum TD buffer service bandwidth R_{opt}^{TD} so that the maximum quadratic distance between $\overline{R}_i^{loss}$ and $\overline{R}_{i,thr}^{loss}$ and between $\overline{R}_i^{delay}$ and $\overline{R}_{i,thr}^{delay}$ is minimized. The problem is solved by taking measures over the given $k-th$ observation horizon (OH), $T_k=\left[t_{k-1},\ t_k\right]$, $k=1,2,..,$ and performing a sequence of bandwidth reallocations, $R^{TD}(t_k)$, $k=1,2,...$, each T_k, based on the gradient method so that $R^{TD}(t_k)\xrightarrow{k\to\infty}R_{opt}^{TD}$. The quantities $\overline{R}_i^{loss}$, $\overline{R}_i^{delay}$, $\overline{R}_{i,thr}^{loss}$ and $\overline{R}_{i,thr}^{delay}$ are actually averaged over each OH, giving origin to the quantities $\hat{R}_i^{loss,k}$, $\hat{R}_i^{delay,k}$, $\hat{R}_{i,thr}^{loss,k}$, $\hat{R}_{i,thr}^{delay,k}$. Bandwidth is adapted through the algorithm Reference Chaser Bandwidth Controller (RCBC) as summarized in Fig. 1.

RCBC increases the bandwidth of the weighted sum of the bandwidth needs to match loss and delay requirements in case there is at least one traffic class demanding bandwidth and decreases the bandwidth of the minimum weighted excess in case all classes show they have too much bandwidth. $step_k$ is the gradient stepsize and is a very important parameter object of the performance evaluation. The details to compute the derivatives $\frac{\partial\hat{R}_i^{loss,k}}{\partial R^{TD}}$ and $\frac{\partial\hat{R}_i^{delay,k}}{\partial R^{TD}}$ appearing in Fig. 1 are reported in [1].

III. OTHER TECHNIQUES USED FOR COMPARISON

The following techniques are used for performance comparison with RCBC. The aim is to highlight RCBC control reliability with respect to other mechanisms taken from the literature and incapable to exactly tune bandwidth values in the presence of dynamic and heterogeneous conditions. a) Proportional Integrative Derivative (PID) controller, whose bandwidth is allocated as:

$$R^{TD}(t_k)=R^{TD}(t_{k-1})+w_k(t_k)\cdot e(t_k)+w_{k-1}(t_k)\cdot e(t_{k-1})+w_{k-2}(t_k)\cdot e(t_{k-2})$$

where $e(t_k)=R_{thr}^{TD}(t_k)-R^{TD}(t_{k-1})$. The weights, which are known as 'proportional gain', 'integral time constant' and 'derivative time constant', are set to 3.00, 1.50 and 1.25, respectively, in this performance evaluation. b) Equivalent bandwidth (EqB). Due to the complexity of the overall input rate process $a(t)$, equivalent bandwidth approaches which use complex mathematical descriptors may be hardly applied in real time. The approach in [10] is applicable in this context for Packet Loss Probability (PLP) control. Let $m_a(t_k)$ and $\sigma_a(t_k)$ be the measured mean and standard deviation of $a(t)$ over the OH; bandwidth is assigned at time t_k, $k=1,2,...$ as $R(t_k)=m_a(t_k)+\sqrt{-2\ln(PLP_{EqB}^{*})-\ln(2\pi)}\cdot\sigma_a(t_k)$. PLP_{EqB}^{*} is the PLP upper bound and is defined as the most stringent PLP requirement out of N TI PLPs (N is the number of traffic classes). c) Ideal Allocation for PLP (Ideal). An ideal allocation technique can be considered for PLP control, which exploits the knowledge of future packet arrivals (though it is not realistic, it can be done via simulation). Knowing packet arrival instants in advance, Ideal computes and allocates the average bandwidth for the next period of time. This assures an ideal bandwidth on average and not in each time instant. d) Ideal Allocation for Packet Delay Probability (IdealDelay). It consists of a continuous monitoring of the buffer occupancy packet by packet. When a given packet experiences a delay higher than the threshold, the service rate of the buffer is instantaneously changed in order to assure the delay requirement. The operation is performed in the (1-PDelay) percentage of the cases.

IV. PERFORMANCE EVALUATION

A. Introduction to tests

Each source is an on-off process with exponentially distributed on and off time durations (mean 1.008 s and 1.587 s, respectively) and basic peak bandwidth of 16 kbps (VoIP traffic according to ITU-T P.59) which is then varied in the tests. Traffic enters an IP buffer whose length and service rate (set by the traffic peak bandwidth) guarantee no packet loss rate. IP traffic is encapsulated in DVB, thus generating the process $a(t)$. $a(t)$ enters the DVB buffer (62 DVB cells), where the loss rate in traffic packets (of 80 bytes each) is measured every OH set to 1 minute. The number of traffic sources is 70. RCBC gradient descent is initialized by the traffic average bandwidth of 70 sources, multiplied by the percentage overhead of DVB. Quantitative metrics such as the average and standard deviation of PLP and bandwidth over the simulation period may help the interpretation of this qualitative behavior. They are identified by: "Average_PLP", "StDev_PLP", "Average_Bw" and "StDev_Bw". Also the percentage of the OH periods where PLP is over threshold ("OverThr") and the average difference between measured PLP and the target ("AverageDiffOThr") are considered.

B. *RCBC validation through parameter variation: loss*

The following analysis regards a general validation by extensively testing RCBC across multiple scenarios and parameter values. Specific attention is devoted to optimal tuning of RCBC stepsize ($step_k$). The final aim is to let RCBC be unequivocally specified offline without further on-line intervention on RCBC parameters as function of the specific working conditions. Tables 1 and 2 synthesize all the performance metrics for PLP by changing: peak bandwidth ("Bp", in kbps) and burstiness ("b", i.e., the ratio between peak and average bandwidth) of the sources, PLP target and buffer size (in DVB cells). The notation RCBC(s) is referred to the adoption of RCBC with stepsize set to s ($step_k = s,\ \forall k$). RCBC_v defines the adoption of the Vogl method (whose tunable parameter is v) to optimize the stepsize [11]: $step_k = v \cdot \left| \hat{R}_i^{loss,k} - \hat{R}_{i,thr}^{loss,k} \right|$ for PLP; equivalent quantities are used for the packet delay (PDelay). The results can be summarized as follows. EqB overestimates the bandwidth need for Bp=16 and it is more precise for Bp=100. PID reveals good performance in all working conditions, but it never satisfies the target as RCBC does. It must be remarked that the Ideal is exactly tuned for the Bp=16 and Buffer=500 case (by properly dimensioning its OH=57s). That is why it fails target satisfaction in all other cases. This highlights the difficulty of tuning the bandwidth allocation on the basis of real time measures, even in the presence of a perfect knowledge of future events. Before entering in more quantitative details, some further considerations are needed. PLP=10^{-3} is the target limit for RCBC functionality with OH size set to 1 minute. The rationale behind this restraint relies on the rare occurrence of loss events around (and below) this limit. Beyond this threshold, the RCBC sampling of loss conditions is too spread over time, thus limiting its applicability. The Buffer=50 case is a limit condition as well because an active connection with Bp=16 produces 1500 packets within each single OH. The resulting effect of all active connections is therefore devastating for a buffer of 50 DVB cells. The same concept holds true for the Bp=100 case, even considering the cases when the buffer contains 500 cells. Nevertheless, RCBC performance decrease is much limited with respect to the other techniques. This robustness assures excellent performance for RCBC in less border-line situations. In overall, RCBC(1) has good performance, but the best compromises among all the cases are RCBC(5) and RCBC_0.5. This is a useful and practical result because a single stepsize covers a large set of working conditions with fine performance, thus avoiding intensive on-line tuning of RCBC sensitivity to losses through the stepsize. A quantitative analysis helps go deep inside this concept. Evidenced values in tables 1 and 2 derive from the application of a Decision Maker (DM) whose decision rule is to choose the first two techniques that achieve the PLP closest to the target and then choose between them the one with the lowest OverThr; the column with two evidenced values indicates the technique chosen by the DM (called DMPLP&OverThr). In all the cases presented, RCBC(1) is chosen 1 time, EqB 4 times, RCBC(5) 5 times, RCBC_0.5 6 times. The defined DM however does not exploit all the other performance metrics.

C. *Use of MADM*

A more powerful procedure is therefore developed to define a large set of DMs by using Multi Attribute Decision Making (MADM) theory [9]. MADM is appropriate for driving automatic decision rules in the presence of multiple performance indicators. Let $\hat{X}_{\kappa j}$ be the performance of the $j-th$ alternative (i.e., a bandwidth allocation technique) under the $\kappa-th$ performance metric; $j=1,...,J$ ($J=6$); $\kappa=1,...,K$ ($K=6$). Let $X_{\kappa j}$ be the corresponding normalized performance: $X_{\kappa j} = \frac{\hat{X}_{\kappa j}}{\sum_j \hat{X}_{\kappa j}}$ and ${}^{id}X_{\kappa j}$ be the ideal performance under the $\kappa-th$ metric defined as: ${}^{id}X_{\kappa j} : j = \arg \min_j X_{\kappa j}$. For each matrix in tables 1 and 2 a DM chooses the j^o alternative under the rule: $j^o = \arg \min_j \sqrt{\sum_\kappa \upsilon_\kappa \cdot \left(X_{j\kappa} - {}^{id}X_{j\kappa} \right)^2}$. This rule is known in MADM as Minimum Distance Utopia Point (MDUP). Intuitively, it indicates the alternative closest to the ideal performance, obtained independently for each metric, as the best alternative. An infinite set of DMs is feasible within the hypercube defined by the weights υ_κ, $\kappa=1,...,K$, being υ_k the level of priority a DM gives to the $\kappa-th$ metric ($\sum_\kappa \upsilon_\kappa = 1.0$). Actually, each human DM has its own sensibility in the scale of priority among the available metrics (an example is the oversimplified DMPLP&OverThr defined above). To obtain a broad-spectrum analysis, a set of DMs (called $\mathrm{DMs}^{\mathrm{MDUP}}$) is defined in Fig. 2. Namely, all the $\mathrm{DMs}^{\mathrm{MDUP}}$ choices are tested by progressively increasing each weight and by equally distributing the remaining level of priority among the other weights. The surprising result from this large set of DMs relies on the highest value of times RCBC_0.5 is chosen as the best alternative. A quantitative metric, capable to synthesize this concept and to emphasize the robustness of RCBC_0.5 against weights variations, is defined as follows. For each matrix $\zeta = 1,...,\mathrm{Z}$ ($\mathrm{Z}=16$) in tables 1 and 2, let ${}^{Max}_{\zeta}\Delta^j_\kappa$ be the highest value of Δ, which is the weight variation defined in Fig. 2, for each υ_κ, for which the $j-th$ alternative is chosen as the best alternative. Weight variation is almost continuous due to the very small Δ_{inc} increase in Fig. 2. The most meaningful result is that alternative j is always chosen in the range $\upsilon_\kappa \in \left[1/K ; {}^{Max}_{\zeta}\Delta^j_\kappa \right]$. So, ${}^{Max}_{\zeta}\Delta^j_\kappa$ not only is a precise indication of the number of times $j-th$ alternative is chosen, but it can be reasonably defined as the Δ-stability metric of $j-th$ alternative in the set of choices of the $\mathrm{DMs}^{\mathrm{MDUP}}$ applied to the $\zeta-th$ matrix and with respect to the $\kappa-th$ weight. Fig. 3 outlines the Δ-stability of RCBC_0.5 and RCBC(5), being those the chosen alternatives for most of the cases. For the sake of synthesis, values in Fig. 3 are representative for the entire set of matrixes in tables 1 and 2; namely, each column represents ${}^{Max}\Delta_{\kappa}^{-0.5}$ and ${}^{Max}\Delta_{\kappa}^{(5)}$ for each single κ-th metric, being ${}^{Max}\Delta_{\kappa}^{-0.5}=\sum_{\zeta}{}^{Max}_{\zeta}\Delta_{\kappa}^{-0.5}$, ${}^{Max}\Delta_{\kappa}^{(5)}=\sum_{\zeta}{}^{Max}_{\zeta}\Delta_{\kappa}^{(5)}$. Δ-stability of RCBC_0.5 is outstanding. RCBC_0.5 is the preferred alternative among the set of $\mathrm{DMs}^{\mathrm{MDUP}}$. For the sake of completeness, the following DMs have been applied with the same MDUP rule and weights:

$\upsilon_{\mathrm{Av\_PLP}}=30\%$, $\upsilon_{\mathrm{StDev\_PLP}}=10\%$,
$\upsilon_{\mathrm{AvDiffOTrh}}=30\%$, $\upsilon_{\mathrm{Av\_Band}}=20\%$, $\upsilon_{\mathrm{StDev\_Band}}=10\%$
and
$\upsilon_{\mathrm{Av\_PLP}}=40\%$, $\upsilon_{\mathrm{StDev\_PLP}}=5\%$,
$\upsilon_{\mathrm{AvDiffOTrh}}=25\%$, $\upsilon_{\mathrm{Av\_Band}}=25\%$, $\upsilon_{\mathrm{StDev\_Band}}=5\%$

Also for these two DMs RCBC_0.5 and RCBC(5) are the chosen alternatives with a larger prevalence of RCBC_0.5. In overall, it is therefore reasonable to consider RCBC_0.5 as the best allocation technique for a very large set of traffic and buffer allocation scenarios.

D. RCBC validation through parameter variation: delay

Even if the results are not shown, as far as delay is concerned, RCBC reveals to be the best compromise between taking PDelay around the target and minimizing the bandwidth effort. PID is always above threshold; IdealDelay is more reliable than Ideal for PLP, but with a significant bandwidth waste in virtue of its packet-by-packet service rate tuning. Differently from the PLP case (where the EqB is sometimes preferred), RCBC is always the chosen technique for the PDelay case, but with a broader range of stepsizes. The application of the $\mathrm{DMs}^{\mathrm{MDUP}}$ (Fig. 2) helps again obtain a powerful synthesis of the results. RCBC_0.5 is the chosen technique for over the 90% of the weight configurations of the $\mathrm{DMs}^{\mathrm{MDUP}}$; this corroborates even more the conclusion achieved for PLP.

E. Role of fading

The fading phenomenon is now considered. A fading process is applied over the same traffic trace used for the previously shown results. The employed fading process (Fig. 4) has been taken from [12], where real attenuation samples are extracted from an experimental data set carried out in the Ka band on the Olympus satellite by the CSTS (Centro Studi sulle Telecomunicazioni Spaziali) Institute (Milan, Italy), on behalf of the Italian Space Agency. The Carrier/Noise Power factor is monitored at each station and, on the basis of its values, different bit and coding rates are applied to limit the BER below a chosen threshold of 10^{-7}. Six different fading classes are defined, corresponding to combinations of channel bit and coding rate that give rise to redundancy factors $\xi_l(t)$, $l=1,\ldots,6$ ($\xi_l(t)\geq 1.0$); $\xi_l(t)$ represents the ratio between the Information Bit Rate (IBR) in clear sky and the IBR in specific working conditions at a given time t. The corresponding bandwidth reduction factor is $\phi(t)=\left(\xi_l(t)\right)^{-1}$. With the data in [12]: $\phi(t)\in\{0.0,\ 0.15625,\ 0.3125,\ 0.625,\ 0.8333,\ 1.0\}$. The bandwidth reduction due to fading, denoted by $R_{real}^{TD}(t)$ (see section II), can be computed as $R_{real}^{TD}(t)=\phi(t)\cdot R^{TD}(t)$; with $\phi(t)=\left(\xi_l(t)\right)^{-1}$. As only the rate $R_{real}^{TD}(t)$ is available for data traffic, $R^{TD}(t)$ has to be tuned over time in order to maintain the required QoS. All system parameters are changed as in tables 1-2 except for the reallocation time period that is reduced to 10s to tackle fading variations whose granularity is 1 minute. The tests with the $\mathrm{DMs}^{\mathrm{MDUP}}$ are repeated. For the PDelay case, very similar considerations can be applied: RCBC_0.5 reveals to be enough robust also in the presence of fading. The considerations outlined above for PLP case should be slightly modified. As the worst fading levels in Fig. 4 (in the period between 5000s and 6000s) have a dramatic impact on the PLP performance, the tunable parameter v of RCBC_v should be increased to 0.7 to achieve performance similar to the tests operated in no fading conditions, while RCBC(5) maintains the same level of robustness for the $\mathrm{DMs}^{\mathrm{MDUP}}$. It is finally worth noting that repeating this analysis with the same fading trace, but substituting the lowest fading reductions of [5000; 6000]s in Fig. 4 with the reductions in [6000; 7000]s, RCBC_0.5 is again the preferred alternative for the $\mathrm{DMs}^{\mathrm{MDUP}}$.

V. CONCLUSIONS

The paper has summarized a bandwidth allocation scheme based only on measures. The efficiency and reliability of the proposed algorithm has been extensively tested over multiple DVB-based satellite scenarios and by analyzing the robustness of the algorithm against parameter variations. The performance evaluation has been carried out through multiple performance metrics. The obtained results have been interpreted through MADM (Multi Attribute Decisions Making) theory and open the door to possible future implementations of the control scheme inside real operative architecture.

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$$if\ \left(\hat{R}_i^{loss,k}-\hat{R}_{i,thr}^{loss,k}\right)>0\ OR\ \left(\hat{R}_i^{delay,k}-\hat{R}_{i,thr}^{delay,k}\right)>0\ for\ at\ least\ one\ i\ then\{$$

$$\Delta_i^{loss}(t_k)=\begin{cases}-2\cdot\left.\dfrac{\partial\hat{R}_i^{loss,k}}{\partial R^{TD}}\right|_{R^{TD}=R^{TD}(t_{k-1})}\cdot\left[\hat{R}_i^{loss,k}-\hat{R}_{i,thr}^{loss,k}\right],\ if\left[\hat{R}_i^{loss,k}-\hat{R}_{i,thr}^{loss,k}\right]\geq 0\\ 0,\qquad otherwise\end{cases}$$

$$\Delta_i^{delay}(t_k)=\begin{cases}-2\cdot\left.\dfrac{\partial\hat{R}_i^{delay,k}}{\partial R^{TD}}\right|_{R^{TD}=R^{TD}(t_{k-1})}\cdot\left[\hat{R}_i^{delay,k}-\hat{R}_{i,thr}^{delay,k}\right],\ if\left[\hat{R}_i^{delay,k}-\hat{R}_{i,thr}^{delay,k}\right]\geq 0\\ 0,\qquad otherwise\end{cases}$$

$$R^{TD}(t_k)=R^{TD}(t_{k-1})+step_k\cdot\sum_{i=1}^{N}\left[\Delta_i^{loss}(t_k)+\Delta_i^{delay}(t_k)\right]$$

$$\}$$

$$else\ \{\ //\ \left(\hat{R}_i^{loss,k}-\hat{R}_{i,thr}^{loss,k}\right)<0\ AND\ \left(\hat{R}_i^{delay,k}-\hat{R}_{i,thr}^{delay,k}\right)<0\ \forall i$$

$$\Delta_i^{loss}(t_k)=-2\cdot\left.\frac{\partial\hat{R}_i^{loss,k}}{\partial R^{TD}}\right|_{R^{TD}=R^{TD}(t_{k-1})}\cdot\left[\hat{R}_i^{loss,k}-\hat{R}_{i,thr}^{loss,k}\right]$$

$$\Delta_i^{delay}(t_k)=-2\cdot\left.\frac{\partial\hat{R}_i^{delay,k}}{\partial R^{TD}}\right|_{R^{TD}=R^{TD}(t_{k-1})}\cdot\left[\hat{R}_i^{delay,k}-\hat{R}_{i,thr}^{delay,k}\right]$$

$$Min\Delta^{-}(t_k)=\Delta_j^{\lambda}(t_k),\ j=\arg\min_i\left\{\left|\Delta_i^{\lambda}(t_k)\right|,\lambda=\{loss,delay\}\right\}$$

$$R^{TD}(t_k)=R^{TD}(t_{k-1})+step_k\cdot Min\Delta^{-}(t_k)$$

$$\}$$

Fig. 1. The RCBC algorithm.

```
$\Delta_{inc}=1\cdot 10^{-2}$;
for $\kappa=1,\dots,K$ {
    $\Delta$=0.0;
    out=false;
    while (!out){
        $\upsilon_\kappa = 1/K+\Delta$;
        $\upsilon_h = \frac{1-w_\kappa}{K-1}+\Delta,\ \forall h\neq\kappa$;
        find $j^o$ : $j^o=\arg\min_j \sqrt{\sum_\kappa \upsilon_\kappa\cdot\left(X_{j\kappa}-{}^{id}X_{j\kappa}\right)^2}$;
        $\Delta$+=$\Delta_{inc}$;
        if ($\upsilon_\kappa\geq 0.99$)
            out=true;
    }
}
```

Fig. 2. The set of $\mathrm{DMs}^{\mathrm{MDUP}}$.

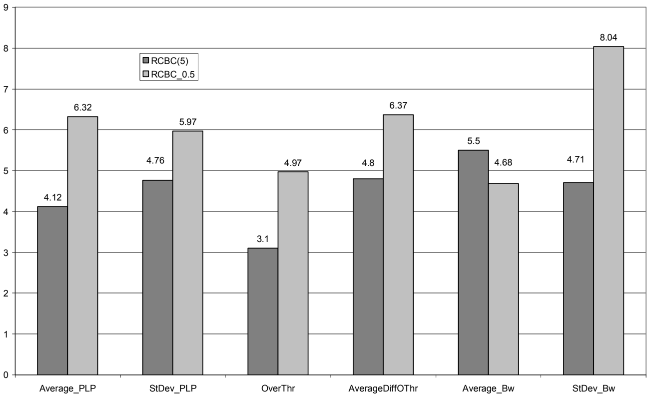

Fig. 3. Δ-stability of RCBC_0.5 and RCBC(5) for each performance metric under the $\mathrm{DMs}^{\mathrm{MDUP}}$.

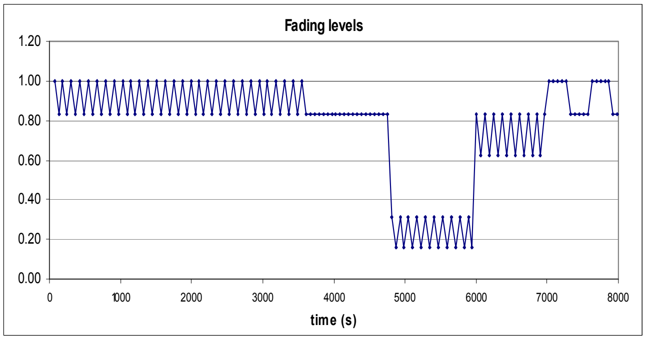

Fig. 4. Bandwidth reduction factor $\phi(t)$).

b=2; Bp=16; Buffer=500; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	4.53E-03	1.59E-03	8.36E-05	1.00E-02	2.20E-03	2.28E-03
StDev_PLP	6.94E-03	1.16E-02	7.76E-04	1.15E-02	5.78E-03	4.99E-03
OverThr_[%]	15	2	0	39	5	6
AverageDiffOThr	1.16E-03	8.18E-04	0	4.70E-03	7.49E-04	3.71E-04
Average_Bandwidth_[Mbps]	1.35	1.38	1.48	1.34	1.39	1.36
StDev_Bandwidth_[Mbps]	0.01	0.03	0.07	0.04	0.04	0.01

b=10; Bp=16; Buffer=500; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	3.58E-03	1.88E-02	2.38E-04	1.04E-02	2.61E-03	4.89E-03
StDev_PLP	1.00E-02	3.05E-02	3.15E-03	1.92E-02	7.19E-03	1.11E-02
OverThr_[%]	10	38	0.6	28	9	16
AverageDiffOThr	2.04E-03	1.41E-02	1.81E-04	6.94E-03	1.20E-03	2.72E-03
Average_Bandwidth_[Mbps]	0.3	0.28	0.38	0.29	0.31	0.3
StDev_Bandwidth_[Mbps]	0.01	0.02	0.04	0.01	0.01	0.01

b=2; Bp=16; Buffer=50; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.03E-02	1.65E-02	4.40E-03	1.06E-02	8.81E-03	1.19E-02
StDev_PLP	5.74E-03	1.30E-02	4.73E-03	6.07E-03	4.69E-03	6.44E-03
OverThr_[%]	44	79	9.6	50	33	56
AverageDiffOThr	2.22E-03	7.11E-03	5.30E-04	2.52E-03	1.32E-03	3.34E-03
Average_Bandwidth_[Mbps]	1.41	1.38	1.48	1.41	1.42	1.4
StDev_Bandwidth_[Mbps]	0.01	0.03	0.07	0.02	0.01	0.02

b=10; Bp=16; Buffer=50; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.79E-02	7.84E-02	1.01E-02	1.32E-02	8.19E-03	1.46E-02
StDev_PLP	1.87E-02	3.92E-02	1.45E-02	1.47E-02	1.21E-02	1.57E-02
OverThr_[%]	56	99	34	43	28	54
AverageDiffOThr	1.06E-02	6.84E-02	5.30E-03	7.00E-03	3.44E-03	7.72E-03
Average_Bandwidth_[Mbps]	0.35	0.28	0.38	0.36	0.38	0.36
StDev_Bandwidth_[Mbps]	0.02	0.02	0.03	0.02	0.02	0.01

b=2; Bp=16; Buffer=500; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	9.98E-04	1.16E-03	4.40E-05	1.35E-03	3.15E-04	2.68E-04
StDev_PLP	3.27E-03	1.09E-02	4.12E-04	3.76E-03	2.43E-03	1.90E-03
OverThr_[%]	18	9	1	23	3	3
AverageDiffOThr	7.67E-04	1.06E-03	3.27E-05	1.07E-03	2.89E-04	2.43E-04
Average_Bandwidth_[Mbps]	1.38	1.39	1.53	1.37	1.49	1.5
StDev_Bandwidth_[Mbps]	0.01	0.03	0.09	0.01	0.03	0.03

b=10; Bp=16; Buffer=500; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	2.30E-03	1.63E-02	2.38E-04	2.55E-03	1.30E-03	3.60E-04
StDev_PLP	7.67E-03	2.84E-02	3.15E-03	7.65E-03	5.03E-03	3.87E-03
OverThr_[%]	13	47	0.6	17	11	1
AverageDiffOThr	2.15E-03	1.59E-02	2.32E-04	2.37E-03	1.17E-03	3.51E-04
Average_Bandwidth_[Mbps]	0.31	0.28	0.42	0.31	0.31	0.38
StDev_Bandwidth_[Mbps]	0.01	0.02	0.04	0.01	0.01	0

b=2; Bp=16; Buffer=50; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	5.03E-03	1.39E-02	2.43E-03	2.43E-03	2.18E-03	1.43E-03
StDev_PLP	5.16E-03	1.23E-02	3.77E-03	4.22E-03	3.09E-03	2.97E-03
OverThr_[%]	88	100	51	59	62	43
AverageDiffOThr	4.07E-03	1.28E-02	1.78E-03	1.69E-03	1.42E-03	8.72E-04
Average_Bandwidth_[Mbps]	1.46	1.39	1.53	1.51	1.51	1.53
StDev_Bandwidth_[Mbps]	0.03	0.03	0.09	0.03	0.03	0.002

b=10; Bp=16; Buffer=50; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.50E-02	7.48E-02	5.48E-03	6.40E-03	5.41E-03	9.16E-04
StDev_PLP	1.78E-02	3.82E-02	1.11E-02	1.23E-02	1.07E-02	9.86E-03
OverThr_[%]	84	99	46	50	53	1
AverageDiffOThr	1.42E-02	7.38E-02	5.00E-03	5.86E-03	4.85E-03	9.07E-04
Average_Bandwidth_[Mbps]	0.36	0.28	0.42	0.4	0.4	1.11
StDev_Bandwidth_[Mbps]	0.02	0.02	0.04	0.03	0.02	0

Table 1. PLP scenario with peak bandwidth (Bp)=16 kbps; changing burstiness (b), buffer size (Buffer) and PLP target (Ploss).

b=2; Bp=100; Buffer=500; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	9.87E-03	1.09E-02	1.90E-03	1.06E-02	8.69E-03	1.09E-02
StDev_PLP	5.80E-03	5.97E-03	2.83E-03	6.56E-03	5.01E-03	6.32E-03
OverThr_[%]	45	52	3	46	38	48
AverageDiffOThr	2.35E-03	2.83E-03	1.09E-04	2.90E-03	1.49E-03	3.04E-03
Average_Bandwidth_[Mbps]	8.63	8.59	9.23	8.62	8.67	8.6
StDev_Bandwidth_[Mbps]	0.08	0.13	0.5	0.14	0.08	0.09

b=10; Bp=100; Buffer=500; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.56E-02	6.42E-02	5.32E-03	1.23E-02	1.00E-02	1.58E-02
StDev_PLP	1.68E-02	3.41E-02	9.84E-03	1.37E-02	1.15E-02	1.48E-02
OverThr_[%]	48	97	20	45	35	52
AverageDiffOThr	8.99E-03	5.43E-02	2.29E-03	6.22E-03	4.33E-03	8.59E-03
Average_Bandwidth_[Mbps]	2.08	1.73	2.4	2.13	2.21	2.1
StDev_Bandwidth_[Mbps]	0.11	0.1	0.23	0.1	0	0.11

b=2; Bp=100; Buffer=50; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.25E-02	2.48E-02	8.29E-03	1.13E-02	9.83E-03	1.39E-02
StDev_PLP	6.78E-03	7.29E-03	5.49E-03	5.36E-03	4.59E-03	6.53E-03
OverThr_[%]	59	98	32	56	44	71
AverageDiffOThr	3.68E-03	1.48E-02	1.49E-03	2.69E-03	1.58E-03	4.71E-03
Average_Bandwidth_[Mbps]	8.98	8.59	9.23	9.02	9.08	8.91
StDev_Bandwidth_[Mbps]	0.15	0.13	0.5	0.13	0.08	0.13

b=10; Bp=100; Buffer=50; Ploss=1e-2

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	2.31E-02	1.08E-01	1.93E-02	1.43E-02	1.40E-02	2.21E-02
StDev_PLP	2.01E-03	3.43E-02	1.89E-02	1.45E-02	1.39E-02	1.60E-02
OverThr_[%]	72	100	58	49	51	79
AverageDiffOThr	1.42E-02	9.76E-02	1.17E-02	6.75E-03	6.47E-03	1.29E-02
Average_Bandwidth_[Mbps]	2.31	1.73	2.4	2.44	2.48	2.33
StDev_Bandwidth_[Mbps]	0.15	0.1	0.23	0.14	0.14	0.12

b=2; Bp=100; Buffer=500; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	4.93E-03	8.60E-03	9.38E-04	2.60E-03	2.08E-03	2.47E-03
StDev_PLP	5.10E-03	5.20E-03	2.28E-03	3.88E-03	3.06E-03	2.87E-03
OverThr_[%]	77	94	23	55	50	58
AverageDiffOThr	4.06E-03	7.63E-03	6.05E-04	1.95E-03	1.46E-03	1.76E-03
Average_Bandwidth_[Mbps]	8.9	8.67	9.5	9.11	9.16	9.08
StDev_Bandwidth_[Mbps]	0.16	0.14	0.65	0.18	0.15	0.11

b=10; Bp=100; Buffer=500; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.25E-02	6.07E-02	2.60E-03	5.48E-03	6.62E-03	3.38E-03
StDev_PLP	1.55E-02	3.31E-02	6.93E-03	1.02E-02	9.91E-03	7.04E-03
OverThr_[%]	71	99	25	40	59	43
AverageDiffOThr	1.18E-02	5.97E-02	2.33E-03	5.04E-03	6.01E-03	2.92E-03
Average_Bandwidth_[Mbps]	2.14	1.74	2.6	2.36	2.31	2.41
StDev_Bandwidth_[Mbps]	0.13	0.1	0.28	0.17	0.15	0.06

b=2; Bp=100; Buffer=50; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	7.85E-03	2.16E-02	5.04E-03	3.69E-03	3.31E-03	1.59E-03
StDev_PLP	6.91E-03	6.75E-03	4.67E-03	4.97E-03	4.12E-03	3.12E-03
OverThr_[%]	97	100	84	73	77	52
AverageDiffOThr	6.85E-03	2.05E-02	4.12E-03	2.83E-03	2.42E-03	8.36E-04
Average_Bandwidth_[Mbps]	9.24	8.67	9.5	9.64	9.63	9.88
StDev_Bandwidth_[Mbps]	0.24	0.14	0.65	0.28	0.2	0.01

b=10 Bp=100; Buffer=50; Ploss=1e-3

	RCBC(1)	Ideal	EqB	PID	RCBC(5)	RCBC_0.5
Average_PLP	1.98E-02	1.04E-01	1.10E-02	7.70E-03	1.04E-02	8.33E-04
StDev_PLP	1.96E-02	3.37E-02	1.45E-02	1.34E-02	1.33E-02	8.93E-03
OverThr_[%]	97	100	75	66	89	1
AverageDiffOThr	1.88E-02	1.03E-01	1.02E-02	6.95E-03	9.54E-03	8.21E-04
Average_Bandwidth_[Mbps]	2.37	1.74	2.6	2.7	2.58	3.81
StDev_Bandwidth_[Mbps]	0.17	0.1	0.28	0.23	0.18	0

Table 2. PLP scenario with peak bandwidth (Bp)=100 kbps; changing burstiness (b), buffer size (Buffer) and PLP target (Ploss)