Dynamic Modeling Of The W-PRDR Algorithm: The Proportional and Derivative Congestion Control
Algorithm for Wireless Networks

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Abstract— In this paper, we propose a new congestion control mechanism for UDP-based traffic over wireless networks. This mechanism uses the “proportional and derivative” admission controller to compute the supported rate at the intermediate routers. It is inspired from ABR-congestion control in the ATM networks and is based on the RTP/RTCP protocol. In the analysis of simulation results under various network configurations, we show that the proposed mechanism ensures a good system stability and a bandwidth fair-share between the competing connections.

Keywords: congestion control, W-PRDR, wireless networks, performance evaluation.

I. INTRODUCTION

At present, there is no universal solution for the well-known congestion and flow control issue in the Internet, whereas new challenges originated by the evolution of computer network and their uses took precedence over the basic network collapse concern that should be prevented by congestion control. Such solutions are divided among different OSI layers: some proposals try to enhance or to propose new transport protocol, while others try to involve the network intermediate routers to solve the network collapse. Particularly, this problem concerns real-time and multimedia traffic, which operate over the UDP protocol, known to be completely devoid of transmission guarantees or any congestion control, which becomes harmful to competing TCP-based traffic present in the network.

This problem is extremely intensified in a wireless context. Indeed, while wired networks are characterized by a stationary topology and a predictable behavior, wireless ones involve links with variable properties as well as dynamic connectivities, which leads to variable bandwidths and high error rates.

Thus, most of usual transport protocols are deployed over wireless networks without taking into account the particularities of the underlying layers. Along with other wireless standards, IEEE 802.11-based networks face numerous insufficiencies such as signal fading, interferences, transmission powers, etc. Moreover, IEEE 802.11-based networks are more complex than wired ones since they rely on random access mechanism (backoff) and a half-duplex channel, so, the retransmission rate highly increases which affects the overall network performances. Therefore, the congestion control mechanisms proposed for the wired networks are no longer applicable in a wireless environment and should be adapted to the new wireless contexts.

Many researches propose to improve the performances of TCP and TFRC over wireless networks by applying loss discrimination algorithms (LDA) in order to distinguish between losses due to congestion and those caused by random wireless errors [1, 2, 3, 4, 5, 6, 7, 8].

Moreover, several other end-to-end congestion control schemes rely on LDA to react to a loss situation in the network. Indeed, PASTRA [12] and VTP [13] take profit of the ROTT loss discrimination algorithm to find congestion signals. In [9], Vicente and al. present the design of LDA+, a loss-delay based congestion algorithm, based on the inter-arrival scheme. An enhancement of the Datagram Congestion Control Protocol (DCCP) is also studied in [10].

Nevertheless, these proposed implicit flow control approaches can be tricky and unreliable over wireless networks. Indeed, besides the complexity of such networks, the performances of LDA-based mechanisms are highly affected by the network topology as well as the number of active flows. Thus, whenever the network features vary frequently, the accuracy of loss classifier is compromised, which often leads to a misclassifying and then a network under-utilization [11]. A comparative study between different LDA is done in [12], where it is shown that they suffer from several insufficiencies.

Another approach is to use an explicit congestion control, which uses precise congestion signaling, where the network explicitly informs the sources the state of congestion by explicit feedback messages. The fundamental advantage of explicit control is that the intermediate routers accurately supervise the stated of the crossed links which allows them to decongest rapidly the queues and decrease congestion delays [13].
Most of explicit congestion control schemes are derived from ABR rate-based congestion control algorithms in ATM networks [14]. In these schemes, the routers explicitly compute the permissible throughput of the bottlenecks and assign to each flow its fairshare according to the available bandwidth. This control method can be easily adapted to a wireless environment given their rapid reaction and their accurate control.

Explicit congestion control over wireless network (XCP [15], RCP [16], QFCP [17]) can solve the end-to-end TCP-like congestion control (link under-utilization, oscillatory throughput, high delays). Thus, an explicit control scheme yields the active connections to converge to a fair throughput with minimal RTT and high utilization of the available bandwidth. ATP (Ad hoc Transport Protocol) is proposed in [18] and is designed for MANET. Authors in [19] present WQFCP as a robust congestion control scheme and try to perform an appropriate capacity estimation of underlying wireless links. Another similar scheme, called EXACT is discussed in [20]. Rahman and al [21] proposed also XRCC as an explicit congestion control scheme for MANET.

If the proposed explicit congestion control schemes succeed to reach efficiency and fairness, none of them is dealing with the stability issue, which is one of the most important concerns in highly dynamic wireless networks.

Motivated by all these reasons, we invested in the design of a new explicit congestion control scheme, called PRDR: The Proportional and Derivative Algorithm which uses a closed-loop control, inspired from servo systems theory. It applies an explicit control at the queues of the intermediate nodes crossed by the controlled connection. We propose W-PRDR as an enhancement of the PRDR to a wireless environment, with an accurate fairshare estimation technique.

The remainder of this paper is structured as follows: we present in section 2 the PRDR traffic control. We provide in section 3 the stability analysis of the closed-loop control of PRDR. Section 4 presents the wireless enhancement that we incorporated in W-PRDR to fit to a wireless context as well as the simulation results. Finally, section 5 concludes this work and draws some perspectives.

II. THE PRDR ALGORITHM

A. Adaptation of PRDR for UDP flow control

The PRDR algorithm was originally designed for ABR control and is based on a closed-loop control rules [22]. In order to adapt the controller to a TCP/IP context, we used the RTP/RTCP (Real-time Transport Protocol/ Real-ime Transport Control Protocol) [23] protocol suite since it can be deployed over the UDP/IP protocol stack. The RTCP protocol is used to convey control information since doesn’t add much overhead in the network. For example, for a transmission rate of 2 Mbps and RTCP source reports sent every 0.1 seconds, the additional control traffic is around 2% of the overall throughput [24].

The PRDR framework is depicted in figure 1 and is as the following: a new UDP-traffic source S connected to a destination D expresses its initial desired rate $R_d$ within a specific field of the RTCP Source Report datagram, which is forwarded hop-by-hop through the intermediate routers until reaching the destination D. Every node in the path from S to D captures the $R_d$ value contained in the RTCP datagram and substitutes it with the local fairshare $q_m$, computed by the router M if and only if it is smaller and then relays this information to the neighbor router $M+1$. Finally, the control datagram reaches the destination D with the minimal value of $q_m$ computed along the connection path. In its turn, the destination feeds back the received fairshare to the source S in a Receiver RTCP Report. This latter adapts its transmission rate according to the received fairshare $q_m$.

B. Granularity of PRDR

Different sources send periodically RTCP source reports every $T_{control}$. The choice of $T_{control}$ sensibly affects both the system transient response (convergence time and initial connection parameters) and the overhead due to the transmission of control information.

Short update periods lead to smaller convergence time, quick system stability as well as less buffer overflows at the intermediate routers. Whether smaller values of $T_{control}$ would highly increases the control overhead. The work realized in [25] provides an in-depth study concerning the choice of the appropriate value of the $T_{control}$ parameter.

C. The dynamics of PRDR

As depicted in figure 2, every intermediate node admits a congestion controller associated to the outgoing link i. This controller computes every period n the fairshare rate $q_f(n)$ based on local information: the difference between the queue occupancy $x_i(n)$ and a fixed threshold $x$, as well as the past control decisions $q_f(n-1), q_f(n-2),..., q_f(n-k)$.

\[ R_d = \min(q_m) \]

**Figure 1. The PRDR framework**
Defining $x^0$, the PRDR algorithm incorporates the principal of AQM (Active Queue Management) based on a closed-loop control which consists in:

- An AQM controller which computes the packets arrival rate to a given queue;
- The queue length at an intermediate node which represents the controlled parameter $x_i(n)$;
- The desired queue length of a given node denoted $x^0$;
- A feedback signal, which represents the sampled system output.

The main goal is to increase on the one hand the system responsiveness (short-term performance) and on the other the system stability and robustness (long-term performance) of the congestion controller. These objectives can be achieved by regulating the queue length which should match with the aimed reference $x^0$.

Thus, the dynamics of the queue $i$ can be described by the following equation:

$$q_i(n+1) = \text{Sat}_\alpha \left\{ q_i(n) - \sum_{j=0}^{J} \alpha_j x_j(n-j) - x^0 \right\} - \sum_{k=0}^{K} \beta_k q_i(n-k), \quad i \in \mathbb{N}$$

Where $J$ and $K$ are non-negative integers and the saturation function is:

$$\text{Sat}_\alpha(z) = \begin{cases} 0 & \text{if } z < 0 \\ \alpha & \text{if } z > \alpha \\ z & \text{otherwise} \end{cases}$$

The saturation function is introduced in order to impose limits of the computed value $q_i(n)$: the zero lower limit keeps a non-negative value for $q_i(n)$, whereas the upper limit $q^0$ maintains a fair rate share between competing flows and prohibits non-congested connections to grab most of their allowed rates.

The work in [25] stipulates that the control gains $\alpha$ and $\beta$ must satisfy the following conditions:

$$\sum_{j=0}^{J} \alpha_j > 0, \quad \sum_{k=0}^{K} \beta_k = 0$$

III. STABILITY ANALYSIS OF THE PRDR CONTROLLER

Stability is an important criterion while designing a congestion control strategy, especially when dealing with multimedia traffic, the most affected by the variation of rate, delay and jitter. To investigate the stability of our proposed scheme, we present in this section the mathematical analysis in order to check out the necessary stabilizing conditions on the control gains $\alpha_i$ and $\beta_i$. For this study, we chose the second order closed-loop for which $J=1$ and $K=1$. Obviously, increasing the values of $J$ and $K$ would confer a more stable system.

Let $Y(n)$ define the state vector as the following:

$$Y(n) = \begin{pmatrix} x(n) - x^0 \\ x(n-1) - x^0 \\ q(n) \\ q(n-1) \end{pmatrix}$$

The system regulated by equation (5) can be rewritten in the following canonical form:

$$Y(n+1) = A Y(n) + \mu B$$

The system’s transfer matrix $A$ is such as:

$$A = \begin{pmatrix} 1 - \alpha_0 & -\alpha_1 & 1 - \beta_0 & -\beta_1 \\ 0 & 0 & 0 & 0 \\ -\alpha_0 & -\alpha_1 & 1 - \beta_0 & -\beta_1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

The closed loop system described by equation (3) is steady if and only if the poles of the characteristic polynomial $P(\lambda)$, defined as the determinant of $\lambda I - A$ have negative real parts [26].

The characteristic polynomial is defined as:

$$P(\lambda) = \lambda^4 + (a_0 - a_1 + 2)\lambda^3 + (a_2 - \beta_0 + \beta_1 + 1)\lambda - a_1 - \beta_1$$

Resolving the polynomial $P$, we draw conditions on values of the control gains $\alpha_0, \alpha_1, \beta_0$ and $\beta_1$ according to closed-loop systems stability criterion stipulated in [26]. The simplified conditions are as follows:

$$-1 < \beta_0 < 1$$
$$\beta_0 (a_0 + 4) - a_1 > 0$$
$$a_0 + a_1 > 0$$
$$a_0 - a_1 < 0$$
$$\beta_1 = -\beta_0$$

The choice of the control gains values could then be driven among the definition domain defined by the five conditions above.
IV. PERFORMANCE EVALUATION OF THE PRDR CONTROLLER

A. Wireless enhancement of the PRDR algorithm

Nominal rates provided by the IEEE 802.11b standard are never achieved, because of CSMA/CA contentions as well as the overhead added by the TCP/IP protocol stack. Consequently, we had to propose and implement an estimation technique to measure the maximal capacity of a wireless cell. This value is vital for the PRDR algorithm since it determines the saturation rate $q^0$ and then the fairshare rate.

By examining the MAC IEE802.11 access control, we used the sending time of a wireless frame $t_i$ as well as the receiving time of the corresponding acknowledgment $t_{ACK}$. For a payload of $S$, the maximal capacity of the wireless cell can be measured by:

$$ C = \frac{S}{t_{ACK} - t_i} $$

Once the maximal capacity is determined, an appropriate value of the saturation rate $q^0$ is:

$$ q^0 = \frac{C \tau}{N} $$

Where $N$ denotes the number of active flows during the control period and $\tau$ is the target utilization rate.

B. Simulation model and configuration

In this performance study, we were interested in the following performance parameters:

- The throughput $r_i$ perceived by the flow $i$ ($1 \leq i \leq N$).
- The instantaneous queue occupancy denoted $x$.
- The system stability $C_i$, which is measured by the variation coefficient of the $r_i$ series.
- The Jain fairness index $f$ [27].

As shown in figure 3, $N$ sources in the wired part of the network initiate $N$ CBR/RTP connections to $N$ destinations respectively situated in the wireless cell. All the sources are connected to the BS via a gateway $G$ with links with a capacity of 15 Mbps and a delay of 10ms. So, the wireless channel represents the single bottleneck in the network. Besides, the wireless nominal rate is 11Mbps, the UDP payload is 1500 bytes. All the simulations last for 300 seconds. The DSDV routing protocol is deployed. The BS implements the second order PRDR algorithm with the following parameters:

<table>
<thead>
<tr>
<th>TABLE I. PRDR PARAMETERS</th>
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<tr>
<td>Queue capacity (packets)</td>
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<td>50</td>
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</table>

The choice of the control gains $\alpha_i$, $\beta_i$, $\gamma_i$ and $\beta_1$ is drawn according to the domain of definition stipulated by the equations (5), (6), (7), (8) and (9).

C. Simulation results

We conducted a series of simulation for six RTP competing flows while varying the control gains values according to the configurations of table 2.

<table>
<thead>
<tr>
<th>TABLE II. CONFIGURATIONS FOR DIFFERENT VALUES OF CONTROL GAINS</th>
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<tbody>
<tr>
<td>Configuration</td>
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<td>C1</td>
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<td>C6</td>
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<td>C7</td>
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</table>

The estimated capacity of the wireless cell when deploying our estimation technique is of 5.2 Mbps. Thus, in the presence of six active flows, the saturation rate $q^0$ computed by the BS is $q^0 = \frac{5.2 \times 0.9}{N} = 780$ kbps. The table 3 provides the measured values of the different performance criterion for the seven configurations cited in table 2. We recall that the values of $C_i$ are given in percentages.

<table>
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<tr>
<th>TABLE III. PERFORMANCE PARAMETERS FOR THE SIMULATED CONFIGURATIONS</th>
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<tr>
<td>Configuration</td>
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Firstly, the fairness index $f$ is close to 1 for all the simulated configurations, which confirms the ability of W-PRDR to allocate fairly the bandwidth between the six competing flows. Secondly, the low values of variation coefficient $C_v$ show that queue occupancy $x$ is maintained close to the average of 40 packets. Besides, we notice that the configuration C2 guarantees a better stability of the queue occupancy where $C_v=20\%$, where the worst value of $C_v$ is recorded for the configuration C4. Third, configuration C2 shows lower values of variation coefficients for all the flows, whereas higher values are shown for the configuration C4. Thus, we can conclude that selecting $a_0=3$, $a_1=2$, $b_0=0.5$ and $b_1=-0.5$ insures the best system stability in terms of queue occupancy as well as the assigned rates. Figure 4 plots the RTP instantaneous rates of the six flows and the buffer occupancy for the configuration 2. Distinctly, all the flows succeed to achieve their fair share of 780 kbps, where the BS buffer occupancy is kept close the fixed threshold $x^0$ of 40 packets.

![RTP instantaneous rates and buffer occupancy](image)

Figure 4. Instantaneous RTP rates and buffer occupancy

V. CONCLUSION AND FUTURE WORK

This paper presents the design and the analysis of a congestion control mechanism (W-PRDR) for UDP traffic over wireless ad hoc networks. The proposed scheme relies on a closed loop control and is inspired from the servo system’s control theory, where each intermediate node in the connection path computes a fair share rate indicating the supported rate that could be assigned to each flow, then, a traffic source has to adapt its transmission rate according to this feedback information. An in-depth analytic study is conducted in order to fix the choice of appropriate control values that ensures the system convergence stability. The W-PRDR mechanism is enhanced with a fair share estimation technique based on the acknowledgment at the MAC level. The proposed scheme is validated by simulations and we show that it succeeds to: i) accurately estimate the fair share rate over a wireless cell on an heterogenous topology, ii) assign fair throughputs to competing flows in the network with maximal fairness index, iii) maintain the queue occupancy level close to the fixed occupancy threshold.

There are several further study topics. First, the behaviour of W-PRDR should be investigated in more realistic network topologies including mobile devices and random input traffic. Second, it is important to carry out a comparative performance study of W-PRDR with similar congestion control, such a cited in [28, 29].

REFERENCES


