2018 26th Mediterranean Conference on Control and Automation (MED)
Zadar, Croatia, June 19-22, 2018

Wireless Data Rate Controller Design for Networked Control Applications

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***Abstract*—This paper presents a design approach for data transfer rate control algorithms meant to assure a prescribed delay in communication channels of wireless networked control systems (NCS). Three types of control algorithms are treated: P, PI and PI + Additive Increase control. Each algorithm is based on delay measurement and computes the transfer rates in the communication channels of NCSs. They are able to compensate the effect of independent communication channels with unknown rates on the expected delay value in the wireless communication medium. By assuming that the communication medium is described by the queue model, the parameters of these control algorithms are explicitly computed such to assure the stability of the closed-loop system and the steady-state control performances. Simulation measurements were performed to compare the behavior of the proposed control algorithms. The applicability of the control approach was tested in a networked bilateral teleoperation system.**

I. Introduction

Recent wireless access points assure more and more available bandwidth in the wireless communication medium. This is necessary to fulfill the requirements of such applications in which high amount of data has to be transmitted among the end-points, such as multiple streaming of high-resolution video data. Despite the enhanced performance of wireless access points, the effective available bandwidth in the wireless communication channels is compromised by many factors such as radio signal strength change or interferences. It is why the regulation of the data transfer rates in such environment remains necessary to avoid network congestion and its undesired consequences such as packet loss, increased delay and jitter, or retransmission [1].

Networked control systems consist of such control loops that are implemented over a communication network: the different components of the control loop transmit information among each other through non-ideal communication channels of dedicated or commercial communication networks such as Wireless Local Access Network (WLAN) or wide area network (Internet). The networked communication allows the distant control of the processes but the undesired effect of the distant communication should also be considered during control system design. It is well known that the delay and delay variation has a negative influence on the stability of the control loop and on the transient control performances [2]. Sophisticated control approaches are necessary to handle the networked communication induced undesired effects [3].

To achieve good performances in networked control systems, beside the dedicated control design, it is also important to assure proper communication conditions. This can be achieved by controlling the data flows in the transmission channels of the communication medium which is used by the networked control system.

The most popular data rate control approach is the Additive Increase - Multiplicative Decrease strategy used by the Transmission Control Protocol (TCP). The stability and performances of this congestion avoidance method were examined in many previous works, see e.g. [4].

Proportional-Integral (PI) rate control approaches were proposed in [5] and [6].

The Active Queue Management (AQM) methods, such as Random Early Detection (RED) or CoDel (Controlled Delay) are meant to assure the controlled drop of the communication packets in the buffers along the communication channels to avoid congestion [7]. The properties of RED-AQM was discussed in the study [8]. Improved AQM control schemes to deal with unwanted variations of communication parameters (the average round-trip time, the link service rate) were introduced in the studies [9] and [10]. A cooperative control approach was also introduced in [11] to solve the queue size control in communication networks.

The enumerated congestion control approaches do not explicitly assure a prescribed communication-independent delay in the communication channels.

In our previous works related to the delay control in wireless communication mediums we have assumed that the access point implements the RED AQM protocol [12], [13]. In this current study the delay control problem was solved without assuming any additional congestion control or congestion prevention mechanism. Different control methods were proposed and analyzed that are able to keep the expected value of the delay in the communication medium near a prescribed value. The proposed algorithms use delay measurement and they can be implemented at the application layer. Based on realistic assumptions, stability conditions for the discussed control algorithms were formulated. The efficiencies of the different control strategies were compared.

In this view, the rest of the paper is organized as follows: Section II presents the communication medium model that is applied to controller design. In section III the control objective is formulated and discusses three control approaches for the proposed control problem. In section IV the proposed switching control algorithm is tested in realistic networked control scenario. Finally, section V concludes this work.

II. Queue model of Wireless Communication Medium

Let a wireless communication medium used by an application that has a number of N communication channels which are implemented over a wireless access point.

Consider that the length of the average queue size in the access point is given by the Lindley's equation, see e.g. [5]:

$$q[k+1] = \max\left(0, q[k] + T_s(R[k] - C)\right), \ q[0] = q_\circ \geq 0 \tag{1}$$

where $T_s > 0$ is the average sending period, $R[k] \geq 0$ denotes the cumulative sending rate through the access point in the kth discrete-time instant, $C > 0$ is the service rate of the wireless access point, and $q_\circ \geq 0$ is a finite constant.

The cumulative transfer rate is considered in the following form:

$$R[k] = R^{(c)}[k] + R^{(d)} = \sum_{i=1}^{N} R_i^{(c)}[k] + R^{(d)}. \tag{2}$$

Here $R_i^{(c)}$ denotes the transfer rate in the ith channel, the value of which can be prescribed within given bounds $0 \leq R_m \leq R_i^{(c)}[k] \leq R_M, \ \forall i, k$. $0 \leq R_m < R_M \leq \infty$ are the given upper- and lower transfer rate bounds. $R^{(d)} \geq 0$ is the cumulative unknown transfer rate value in the channels of other applications that may use the same wireless communication medium such that $0 \leq R^{(d)} \leq R_M^{(d)} < \infty$. It is assumed that $R^{(d)}$ is piecewise constant.

In the case of the moving end-nodes, which is a common situation in the case of wireless communications, the service rate in the access point cannot be considered constant. It is because in the case of moving agents the radio signal strength is time-varying. The wireless access point automatically adapts the available service rate (C) in function of the sensed or estimated radio signal strength. Here it is considered that $0 < C_m \leq C \leq C_M < \infty$ is piecewise constant and unknown by the applications. It is assumed that the intervals among changes in the value of C are considerably longer than T_s.

The average discrete-time lag in the communication medium can be computed as, see e.g. [10],

$$\delta[k] = \left(\frac{q[k]}{C} + T_P\right)/T_s \tag{3}$$

where the integer value of $\delta[k]$ is the number of average sending periods that characterizes the discrete-time delay in the communication medium and T_P is the propagation time in the wireless communication medium.

III. Rate Control Approaches

A. Control Problem

Consider that the average delay in the communication medium can be modeled by the equations (1) and (3).

Control objective: determine $R_i^{(c)}[k]$ such that the value of the discrete-time lag δ is always bounded and converges under a predefined limit value $\varepsilon > 0$. Here $\varepsilon \geq T_P/T_s$.

The realization of the formulated control objective has two important consequences.

First, if the application implements a networked control loop with bounded communication delay, better control performances can be assured. It is known that the delay has a negative impact on the stability and robustness of networked control systems [2]. If the communication delay can be kept under certain limits, such controllers can be designed that are able to assure better tracking performances beside stability.

Second, it is known that high communication lag is an indicator of the congestion in the communication medium [1]. The congestion induces such undesired effects such as increased number of communication packet losses, retransmission or jitter. Consider that ε is chosen such that its value corresponds to normal (congestion-free) communication condition. If it can be assured that the delay remains under this given limit value by the reduction of the amount of transmitted data, implicitly the congestion is avoided.

From the equation (1) it can be seen that, when $R[k] < C$ for a sufficiently long period of time, the queue size, and consequently the lag converges to zero. Otherwise, the data transfer rate values take such values that the queue size remains over zero, i.e. the dynamics of the lag is given by:

$$\delta[k+1] = \delta[k] + \frac{1}{C} R^{(c)}[k] + D, \ \delta[0] = \left(\frac{q_\circ}{C} + T_P\right)/T_s \tag{4}$$

where $D = \left(R^{(d)} - C\right)/C$ is piecewise constant.

To assure the feasibility of the control objective, it is assumed that

$$R_M^{(d)} < C_m. \tag{5}$$

B. Proportional Control

Let the controlled rate be computed in function of the measured delay as

$$R^{(c)}[k] = K_P\left(\delta_{ref} - \delta[k]\right), \ K_P > 0. \tag{6}$$

$\delta_{ref} > 0$ is the prescribed discrete-time lag.

With the proportional controller above the dynamics of the controlled system is given by:

$$\delta[k+1] = \left(1 - \frac{K_P}{C}\right)\delta[k] + \frac{K_P}{C}\delta_{ref} + D. \tag{7}$$

The controlled discrete-time system above is stable if $|1 - K_P/C| < 1$. This condition can be assured by choosing the controller gain $K_P < 2C_m$.

The steady-state value of the delay reads as the integer value of

$$\delta^* = \delta_{ref} + \frac{R^{(d)} - C}{K_P}. \tag{8}$$

By (5), it can be seen that $\delta^* \leq \delta_{ref}$. If K_P is chosen such that the stability condition is satisfied and $\delta_{ref} < \varepsilon$, the proportional control assures the prescribed control objective.

C. Proportional-Integral Control

The rate controller which contains the integral of the control error

$$e = \delta_{ref} - \delta[k] \tag{9}$$

can be formulated as

$$e_I[k+1] = e_I[k] + K_I e[k], \tag{10}$$

$$R^{(c)}[k] = K_P e[k] + e_I[k]. \tag{11}$$

where $K_I > 0$, $K_P \geq 0$.

By (4), the error dynamics with PI control can be computed as

$$\begin{bmatrix} e[k+1] \\ e_I[k+1] \end{bmatrix} = \begin{bmatrix} 1 - \frac{K_P}{C} & -\frac{1}{C} \\ 1 & K_I \end{bmatrix} \begin{bmatrix} e[k] \\ e_I[k] \end{bmatrix} + \begin{bmatrix} D + \delta_{ref} \\ 0 \end{bmatrix} \tag{12}$$

The characteristic polynomial of the system (12) reads as

$$P(\lambda) = \lambda^2 + a_1\lambda + a_0. \tag{13}$$

$$a_1 = 1 - K_I - K_P/C. \tag{14}$$

$$a_0 = 1/C + K_I(1 - K_P/C). \tag{15}$$

According to Jury's sufficiency condition [14], the system is stable if K_P and K_I satisfy:

$$-1 < a_0 < 1. \tag{16}$$

If $D + \delta_{ref}$ is constant and the controller parameters are chosen such that the relation (16) is satisfied, for $\delta_{ref} < \varepsilon$ the control objective is ensured.

D. Switching Control (PI + Additive Increase)

According to the previous subsections, the control objective, related to the maximum communication lag, can be assured by applying conventional control algorithms with appropriate parametrization. However, other objectives can also be formulated to assure proper communication conditions in the wireless communication medium. It is also desirable to assure as good throughput in the wireless access point as possible.

The *communication objective* is formulated as: assure that in the communication channels of the application the cumulative transfer rate $R^{(c)}[k]$ takes as high value as possible.

To satisfy both the control objective and the communication objective, multi-criterial optimization approaches can be applied, such as the lexicographical optimization method [15], [16]. According to this optimization method, the objectives are arranged in order of importance. The procedure finds the optimum solution of the more important objectives before dealing with the others.

Here it is considered that the control objective has higher importance as the communication objective. In the view of the lexicographical optimization method, the transfer rate is modified in function of the delay applying such a control algorithm that can solve the control objective. Whenever $\delta < \delta_{ref}$ the communication objective is treated, by increasing the transfer rate.

This strategy can be implemented as a switching control law in the following form [17]:

$$R^{(c)}[k] = \begin{cases} R^{(c)}[k-1] - K_I\delta[k] \\ \quad - (K_P - K_I)(\delta[k] - \delta[k-1]), & \text{if } \delta \geq \delta_{ref}, \\ R^{(c)}[k-1] + r[k], & \text{otherwise} \end{cases} \tag{17}$$

where the increment is $r[k] > 0$ and $\delta_{ref} < \varepsilon$.

When $\delta \geq \delta_{ref}$, the switching control is equivalent to the PI algorithm with zero reference. Otherwise, the control algorithm above applies the additive increase strategy.

The advantage of the switching control in comparison to the PI control is that it does not necessarily increase the lag the prescribed value. If $\delta < \delta_{ref}$ the rate is increased only if this is necessary for the application.

Remark: During the control implementation it should also be considered that the control signal (computed transfer rate) has to be positive regardless of the applied control strategy. The implementation forms of the control algorithms are $R^{(c)}[k] =: \max(R^{(c)}[k], 0)$.

E. Control Effort Distribution

The control input represents the sum of the transfer rates in N different channels, $R^{(c)}[k] = \sum_{i=1}^{N} R_i^{(c)}[k]$. For the implementation of the proposed control strategies it is not necessary to modify the transfer rates in all the channels in the same extent.

A constant priority value $p_i > 0$ is attached to each channel such that $\sum_{i=1}^{N} p_i = 1$. The priority shows the importance of the channel: in the channels with high priorities it is more important to ensure higher transfer rate values.

During the implementation of the control algorithms the idea of *roulette wheel selection strategy* [18] can be followed: if the control strategy prescribes the increase of the transfer rate, the rate in the channel with higher priority is modified with a probability equal to the priority value. If the decrease of the cumulative transfer rate is necessary, the rate value will be decreased with higher probability in such channels that have lower priorities.

F. Simulation Measurements

To examine the efficiency of the investigated control approaches, simulation experiments were performed. The communication medium was modeled by the equations (1) and (3). The following parameters were taken: $T_s = 0.01$s, $T_P = 0.001$s, $C = 1500$ packet/s, $C_m = 1000$ packet/s, $R^{(d)} = C_m/2$ packet.

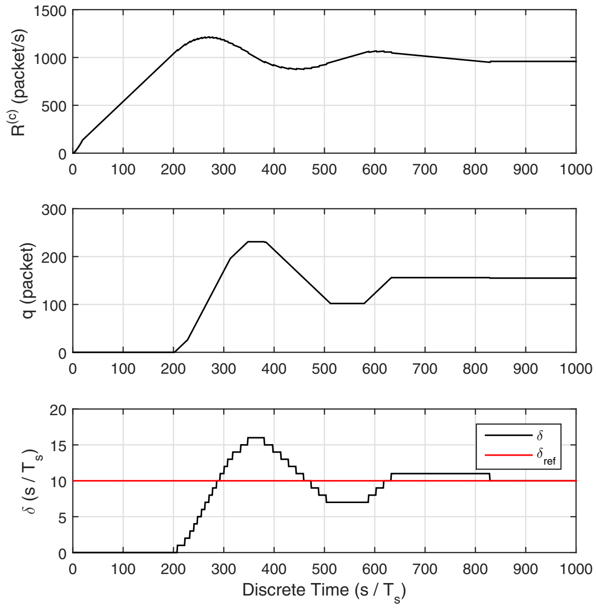

Fig. 1. PI control simulation

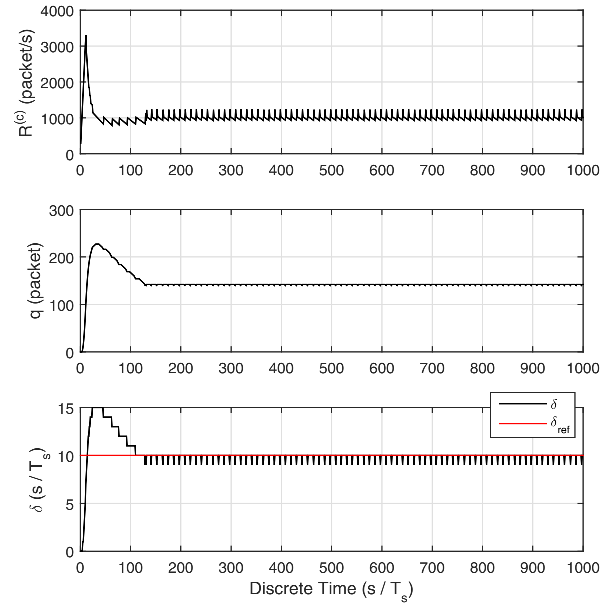

Fig. 2. Switching control simulation

Both the PI control and the switching control algorithms were tested with the following parameters: $\delta_{ref} = 10$, $K_P = 10$, $K_I = 0.5$, $r = 300$. Simulation results are presented in the Figures 1 and 2. The sufficient stability condition (16) with these parameters is satisfied as $a_0 = 0.503$. The simulation measurements show that both control approaches assure that the communication lag reaches the prescribed value.

The switching control allows an additional tuning possibility when the lag δ is under its prescribed value. By increasing the parameter r, the transfer rate values in the delay-critical channels reach faster their nominal values. As a consequence, better settling time in the controlled system can be achieved.

IV. Case Study

A. Video-supported Bilateral Teleoperation Systems

Bilateral teleoperation is an efficient approach for remote control of robotic manipulators or mobile robots [19]. In these systems the distant robot is controlled by a human operator based on haptic and visual information. The human operator generates the position and velocity signals using a haptic device [20] that will serve as reference signals for the controller of the remote robot. The position and velocity are typically sent form the human operator (master side) to the remote robot (slave side) through a communication network. In the case of teleoperated mobile robots the information should be sent through a WLAN. When the robot is in contact with its environment, the forces and torques are measured and sent back to the human operator. The force is displayed to the human operator by the haptic device.

The human operator also has video information about the remote robot. The video information can be captured using cameras that are mounted on the robot, or placed in the environment of the robot. The video information can be sent back in the same communication medium using dedicated channels.

The bilateral teleoperation systems are sensible to the communication lag. Large delay between the master and slave side can induce instability in the control loop consisting of position command and the haptic feedback. The stability in the presence of large communication delay can be assured by extra damping terms in the controllers of the slave robot and the haptic device [21]. The larger the delay the grater damping is necessary [22]. However, the additional damping term applied to the force signal received at the master side compromises the realistic display of the haptic feedback. It is why it is important to control the delay in such networked robotic system and to assure as small communication lag as possible.

The communication channels, necessary to implement a bilateral teleoperation system, are presented in Figure 3.

The channel PCh from the master side to the slave side is applied to send the position and velocity information to the remote robot. The force channel FCh from the slave side to the master side is used to transmit the force feedback to the haptic device operated by the human operator. In these channels the information is typically sent periodically with a sending period comparable to the control period applied by the slave robot.

Through the video channels (VCh) video information is sent from the slave side to the master side. The rate in these channels can be modified by changing the sending

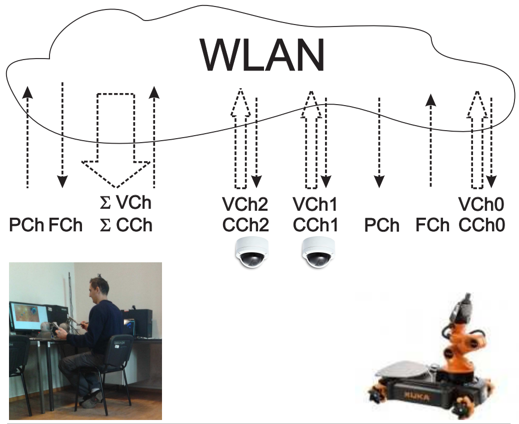

Fig. 3. Communication channels in the video-supported teleoperation system [23]

period, or by modifying the quality of the sent image (e.g. by applying different compression rates to the video frames). These modifications will change the quality of the video displayed to the human operator. However, if the quality change is within certain limits, the teleoperation task is not compromised.

The total transfer rate in the communication medium of a teleoperation system is

$$R[k] = \sum_i R_i^{(V)}[k] + R^{(P)} + R^{(F)} + R^{(d)} \qquad (18)$$

where $R_i^{(V)}$ is the transfer rate in the ith video channel, $R^{(P)}$ is the transfer rate in the position channel, and $R^{(F)}$ is the transfer rate in the force channel.

The video transfer rates are the controlled ones, the transfer rates in the position channels can be considered as (known) disturbances.

To each video channel a priority can be attached. Consider the scenario when the teleoperated mobile robot is used in indoor environment. On the robot a video camera is placed. In each room other video cameras are present. To the video channels used by the on-board camera and by the cameras, the field of vision of which the robot moves, high priority values can be attached. To the communication channels of other cameras lower priority values can be attached. Hence, for rate control in video supported teleoperation systems, the control effort distribution method, presented in subsection III-E, is applicable.

B. Experimental Measurements

A bilateral teleoperation system was implemented in which a KUKA Youbot mobile manipulator served as a slave robot and its remote control was implemented by using a Sensable Phantom Omni haptic device. Three Microsoft USB cameras were used to monitor the actions of the robot. On the robot an on-board camera was fixed. Two surveillance cameras were placed in the environment of the robot. The size of the captured video frames is 640 × 480 pixels and the color resolution of the frames is 24 bit.

The position, force and the three video channels (VCh0, VCh1, VCh2) are implemented through a TPLINK TL-WR941ND wireless access point. The sending periods in PCh and FCh were chosen 5ms. The video frames were captured at 20 Hz rate and there were sent in every 50ms from the master side to the slave side.

To each video channel a priority value attached. The video channel of the on-board camera had the higher priority: $p_0 = 0.5$. The priority value for the environment cameras were taken as: $p_1 = 0.35$, $p_2 = 0.15$.

The proposed control algorithm (17) was implemented at the slave side, where the transfer rates in the video channels can be modified. The communication delay was measured in the delay-critical PCh channel by using the methods presented in [24].

JPEG compression was used to modify the rates in the video channels. By applying different JPEG compression on the frames, the amount of the sent video data can be controlled. In the software implementation the JPEG compression is an integer between 0 and 100. The JPEG compression rate was computed by the switching control algorithm (17) based on delay measurements.

The reference delay value for the control algorithm was taken $\delta_{ref} = 10ms$.

The UDP protocol was chosen to implement all the communication channels. In this view the proposed data rate control algorithm also served as a congestion avoidance algorithm in the wireless communication medium.

The experimental measurement results are presented in Figure 4.

During the experiments a disturbance data channel was also started at $t = 60$s in the same wireless communication medium. A TCP disturbance channel was used as disturbance, generated by the IPerf software.

The first subplot shows the controlled delaye value, the second shows the packet delay variation $R\_PDV = |\delta[k] - \delta[k-1]|$. In the third subplot the control signal (computed JPEG compression - u) can be seen. The fourth subplot shows the transfer rates in the control channels and in the disturbance channel. The transfer rates were monitored using an Aircap NX wireless data packet capturing device together with the Wireshark network packet analyzer software. The rate measurements were made independent of the teleoperation software.

The experimental measurements show that the proposed control algorithm is able to assure the prescribed value of the delay in the communication channel.

The control signal reacts to the disturbance, it is able to compensate the effect of the disturbance transfer rate on the communication delay. When the TCP channel was started in the video channels the transfer rates are reduced by the proposed rate control algorithm such to guarantee the prescribed average delay.

V. Conclusions

A control design approach was introduced to determine the parameters of different data rate control algorithms

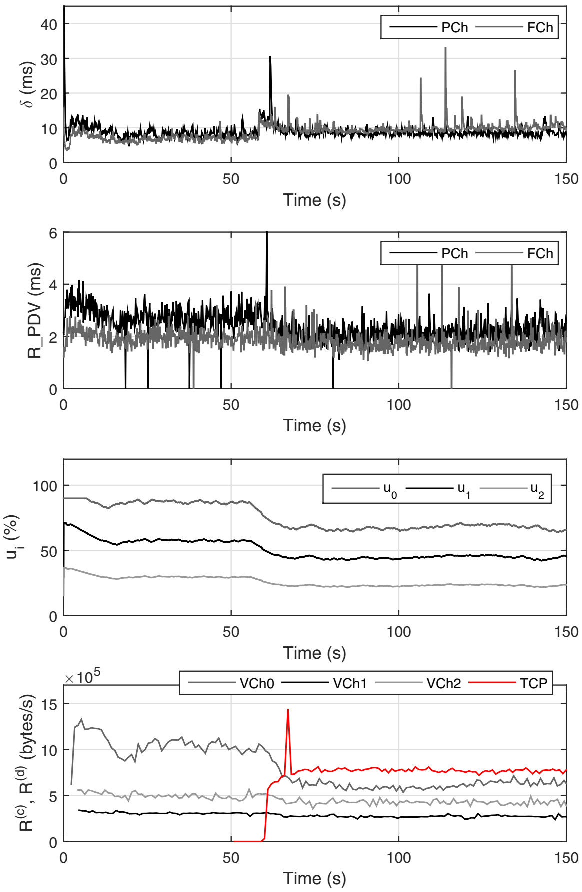

Fig. 4. Real-time data rate control measurements

which are meant to assure that the delay in the communication channels of networked control systems stay under a predefined limit. The design is based on the discrete-time queue model of the communication channels and no explicit knowledge on the queue parameters is necessary for the control design; only the limit values of the parameters have to be known to design stable data rate control. Both conventional (P, PI) and switching control algorithms were studied. The simulation and experimental measurements show that the switching control that combines the additive increase strategy with PI control is suitable for keeping the communication lag under a prescribed limit. This proposed control approach is applicable to real networked control applications such as bilateral teleoperation systems.

Acknowledgments

This work was supported by the Romanian National Authority for Scientific Research and Innovation under Grant number PN-III-P2-2.1-BG-2016-0140, NKFI-6 fund through project K120366 and MTA Bolyai Scholarship.

The first author's research was also supported by a grant of the Romanian National Authority for Scientific Research, CNCS - UEFISCDI, project number PN-II-RU-TE-2011-3-0005.

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