BIO-INSPIRED RATE CONTROL FOR MULTI-PRIORITY DATA TRANSMISSION OVER WMSN

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ABSTRACT

The irrational use of limited network resources in conjunction with the unpredictable nature of traffic load injection in wireless multimedia sensor networks (WMSN) may lead to congestion. Traditional transmission schemes were not designed for supporting prioritized QoS, especially not for guaranteeing strict QoS required by real-time services such as voice and video. To overcome these deficiencies, an optimized rate control approach is proposed for multi-priority data transmission based on the extended Lotka-Volterra competitive model. The key idea is, when some new traffic flows are initialized and injected into the WMSN due to unexpected events, a novel bio-inspired rate control (Bio-RC) approach is designed to consider their effects on the system stability according to the limited network resources and competitions with others traffic flows, ensuring that the system will rapidly converge to a global and stable equilibrium point (EP) and all traffic flows are of peaceful coexistence and differentiated with QoS and priorities. At the same time, the network resources can be utilized adequately and congestion can be brought down or avoided effectively. Extensive simulations reveal that the proposed approach achieves adaptability and scalability to dynamic network traffic load, and coexistence with service differentiation for data flows.

INTRODUCTION

The rapid development of low-cost hardware (e.g. smart phones and CMOS cameras) has fostered the implementation of Wireless Multimedia Sensor Networks (WMSN), i.e. networks of wirelessly interconnected devices that are able to ubiquitously retrieve multimedia content such as video and audio streams, still images, and scalar sensor data from the environment[1]. WMSN will not only enhance existing sensor network applications (e.g. localization, tracking, smart home, and environmental monitoring), but also enable several new applications such as multimedia surveillance sensor networks, traffic avoidance/enforcement and control systems, industrial process control, advanced health care delivery, etc.

However, in order to support most of the above applications, the traditional sensor network paradigm should be rethought in view of the need for protocols and mechanisms to transmit multimedia content with a certain level of QoS. The various applications envisaged on WMSN will have different QoS requirements. Therefore, service differentiation for multi-priority data flows initiated from numerous kinds of applications should be supported and guaranteed[2,3]. For example, the applications can be real-time and delay-tolerant applications, and loss-tolerant and loss-intolerant applications[1].

In this paper, a self-adaptive and decentralized bio-inspired priority-based rate control (Bio-RC) approach is proposed, which is based on the extended Lotka-Volterra (LV) competitive model. And the sending rate of each flow is regulated by the varying network conditions and data flow trends of a local network. It aims to provide efficient resource allocation and smooth rate control while maintaining service differentiation and coexistence for multi-priority data flows, and also providing graceful performance as some traffic load is injected or removed. Moreover, global system stability and convergence is investigated based on the model parameters selection as well as interactions among competing data flows.

The remainder of this paper is organized as follows: Section II analyzes the related work for multi-priority data transmission over WMSN. In Section III, we introduce the ecosystem in rate control for data transmission (i.e. the extended LV model). Section IV proposes the bio-inspired rate control approach for multi-priority data transmission. We presents the performance assessment of the proposed approach in Sections V. The paper is concluded in Section VI.

MULTI-PRIORITY DATA TRANSMISSION

With rapid development and miniaturization in hardware, a sensor node of a WMSN may have e-

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quipped with various types of sensors which gather different kinds of data. It is observed that the data collected may have different levels of importance and priority, so the WMSN should allocate more bandwidth in disseminating packets with a higher priority. For example, whenever an important event occurs in a safety system, some alarm messages (e.g. video streaming or still image) detected by the sensor node should be priorly sent to the monitor or user. And usually this kind of higher priority traffic is bursty and unpredictable, i.e. some high priority traffic is generated only within a short period of time while other low priority traffic usually exists in the network and produce large amount of packets periodically. However, most of current rate control schemes or algorithms[4,5,7,13,14] for WMSN assume that all the traffic flows are assigned with the same level of priority, and the network resources (e.g. bandwidth) are allocated to all of the existing flows fairly, which cannot provide service differentiation for multiple different classes of applications.

Differentiated QoS requirements have recently been considered for WMSN[6,8-11], and one important research question is how to estimate the maximum sending rate that can be allocated to a new injected flow while it will be contending with other existing flows, and estimate the decrease of the throughput and the increase of the delay of existing flows under the new arrival flow. There have been quite a few rate control approaches for priority-based data transmission proposed by academic and industry, which can be broadly classified into three categories based on the collected information: 1) parameter-based approaches [9,10] (e.g. contention window size); 2) performance-based approaches[8] (e.g. throughput, delay); 3) hybrid approaches[11]. Although these approaches have achieved success in their respective target applications, many of them are application specific.

ECOSYSTEM IN RATE-CONTROL FOR DATA TRANSMISSION

The nature of the world shows that the dynamics of many biological systems and laws governing them are based on a surprisingly small number of simple generic rules which yield collaborative and effective patterns for resource management, task allocation and social differentiation without the need for any externally controlling entity[12].

Since the population size of each species changes over time as a result of numerous interactions with other species and limited resources in their environment (i.e. food, water and territory), this process can be investigated by being modeled with a simple balance equation. The well-known Lotka-Volterra (LV) model originally focusing on ecological population dynamics, which is proposed by Lotka and Volterra, has been extensively investigated in the literatures [5,12-14]. The main idea of LV model is that when two or more species live in a ecosystem and share the limited environment resources, they usually compete each other to survive and may coexist with limited resources. This idea of LV competitive model is first borrowed to analyze the optimum sending rate of each data flow is first borrowed for single-priority data transmission in [5,13,14], in which a WMSN is considered as a simplified prototype of an ecosystem.

It is well-known that a general ecosystem comprises of multiple species, which live in proximity and interact with resources and competitors for the objective of survival and coexistence. Similarly, a traditional WMSN involves a number of wireless nodes. Each node is able to initiate a data flow with a different priority, but has a limited ability to access the shared wireless bandwidth. Then the data flows in a WMSN play the role of species in an ecosystem that compete with each other for limited network bandwidth, while passing through a set of intermediate nodes to the monitor or user. Then the sending rate of each flow can be seen as the population size of each species. According to the integrated competitions from other data flows [5,14], the sending rate evolution of each flow can be described as follows:

$$\frac{dx_i(t)}{dt} = x_i(t)\left(r_i - \frac{\beta_i r_i}{N_i}x_i(t) - \frac{r_i}{N_i}\left(\sum_{j=1,j\neq i}^{n} a_{ij}x_j(t)\right)\right) \tag{1}$$

where $x_i(t)$ is the sending rate of traffic flow i at time t ($x_i(t) > 0$). r_i indicates the growth rate intensity of data flow i. N_i is the total network bandwidth. The sending rate of each flow reproduces proportionally to the current sending rate of the same type flows, by the intra-specific competition coefficient β_i. N_i/β_i is the maximum sending rate of flow i that can be sustained in the WMSN under the absence of other flows competing for the limited bandwidth.

If the WMSN is a single-priority network (i.e. without considering the differentiated QoS requirement of multiple data flows), then the inter-specific competition coefficient of any two flows i and j are constant, $a_{ij} = a$, and the intra-specific competition coefficient equals to the inter-specific coefficient, $\beta = a$. This type of single priority network is widely-used in the current protocols of wireless nodes and routers. Therefore, the value of sending rate generated by each data flow converges to a global and stable state x_i^* [5,14] given by

$$x_i^* = \frac{N}{a\,(n-1)+a} \tag{2}$$

However, this rate control approach focuses on single-priority data transmission with a result of fairly sharing the wireless bandwidth, so it only can work on the networks without considering the differentiated QoS requirements. Therefore, it can not be satisfied by multi-priority data transmission in WMSN. To the authors' knowledge, there are not any works by using the extended LV model to deal with multi-priority data transmission, especially in WMSN.

BIO-INSPIRED RATE CONTROL APPROACH FOR MULTI-PRIORITY DATA TRANSMISSION INWMSN

In order to support multi-priority data transmission, a Bio-inspired rate control (Bio-RC) approach is proposed based on the extended LV model shown in Equation (1). It is found that the species of an ecosystem have different positions in its biological chain, i.e. some species are much stronger and more powerful than others, they will consume more resources from the surrounding environment. This phenomenon can also been seen in WMSN, that the data flows with a higher priority are much more important than ones with a lower priority, and bandwidth of the network will be priorly allocated to the data flows with the highest priority, which means that the packets of the flow with the highest priority have more opportunities to be transmitted. And in analogy with an ecosystem, the goal of a WMSN is expected to achieve service differentiation and coexistence of all data flows.

According to the above analysis, there are five correspondences between a WMSN and an ecosystem, i.e. a) the data flows n initiated by each node refer to competing species; b) the sending rate $x_i(t)$ of flow i corresponds to the population size of species i; c) the sending rate of each flow is influenced by inter-actions among competing flows as well as the available bandwidth, named inter-specific or intra-specific competition coefficient a_{ij}; d) the growth rate intensity r_i of each flow refers to the growth rate intensity of each species; e) the limited bandwidth N of a WMSN plays the role of the natural resource in the ecosystem, which is ignored by the original Lotka-Volter model.

As discussed in Section II, WMSN will need to support service differentiation for various applications with a certain level of QoS requirement, such as real-time or delay-tolerant applications, and loss-tolerant or loss-intolerant applications. We consider four categories of data flows from highest priority to lowest priority in this paper: real-time loss-intolerant traffic, real-time loss-tolerant traffic, delay-tolerant loss-intolerant traffic and delay-tolerant loss-tolerant traffic. Each traffic class is assigned with a different priority. To simplify the notations, we rename four categories of traffic as Prio_4, Prio_3, Prio_2 and Prio_1 from the highest priority to the lowest priority in the rest of this paper.

So this paper adopts the above idea in the design of rate control approach for competing flows of data in WMSN, specially for data flows with different levels of QoS requirements. The proposed Bio-RC approach is based on the extended LV competitive model, and describes competitions among data flows with objective of coexistence, where the sending rate of each flow is influenced by the presence of other data flows and allocation of available network bandwidth. Moreover, the Bio-RC approach is expected to meet differentiated QoS requirements for various applications based on their priorities, and quickly converge to a global stable equilibrium point (EP) under randomly changing network conditions.

To support the service differentiation between the above four categories of traffic, four assumptions are made as follows:

1. The effect of inter-specific coming from flow i to flow j is identical to the effect from flow j to flow i with the same value of i and j, i.e. the coefficient $a_{ij} = a_{ji}$.
2. The effect of intra-specific of all traffic flows is a constant, i.e. the coefficient $a_{ii} = \beta (i = 1, ..., n)$ where n is the number of all traffic flow.
3. The growth rate intensity of any data flow i is a constant, i.e. the coefficient $r_i = r$.
4. The maximum sending rate of each flow is equal to the limited bandwidth of a WMSN, i.e. the coefficient $N_i = N$.

Then the extended Lotka-Volterra model of WMSN as shown in Equation (1) can be rewritten in vector form:

$$dx/dt = X \cdot (B - Ax) \tag{3}$$

where $X = diag\left(x_1(t), x_2(t), \cdots, x_n(t)\right)$, $B = (r, r, \cdots, r)^{\mathrm{T}}$ is an n-dimensional constant vector, and $x = (x_1(t), x_2(t), \cdots, x_n(t))^{\mathrm{T}}$ is also an n-dimensional state vector of all data flows in WMSN, and superscript $^{\mathrm{T}}$ denotes the transpose operation. $A = (a_{ij})_{n \times n}$ is an $n \times n$ real symmetrical matrix based on the assumption $a_{ij} = a_{ji}$, i.e.

$$A = \frac{r}{N} \begin{bmatrix} \beta & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{12} & \beta & a_{23} & \cdots & a_{2n} \\ a_{13} & a_{23} & \beta & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{1n} & a_{2n} & a_{3n} & \cdots & \beta \end{bmatrix} \tag{4}$$

For data flow i, its sending rate $x_i(t)$ can be calculated as follows (see the Appendix):

$$x_i(t) = \frac{w(t) \cdot x_i(0) \cdot e^{\frac{w(t)r}{N}t}}{w(t) - \beta x_i(0) + \beta x_i(0) \cdot e^{\frac{w(t)r}{N}t}}, \tag{5}$$

$$w(t) = N - \sum_{j=1, j \neq i}^{n} a_{ij} x_j(t)$$

Then the sending rate of each flow is regulated on the basis of Equation (5) for $i = 1, 2, ..., n$. And the stable equilibrium point x^*, i.e. the desirable sending rate of each flow, can be obtained as follows

$$X^* \cdot (B - Ax^*) = 0 \tag{6}$$

In the presence of all data flows with different priorities, there will be three combinations of equilibrium points: all data flows coexist, all data flows extinct, and the combination of some data flows can be transmitted and some can not. From a network system point of view, the sending rates of all data flows must be non-negative. Therefore, Equation (6) can be simplified as

$$B - A \cdot x^* = 0$$

Parameter selection of the proposed multi-priority approach is discussed in detail in the next Section.

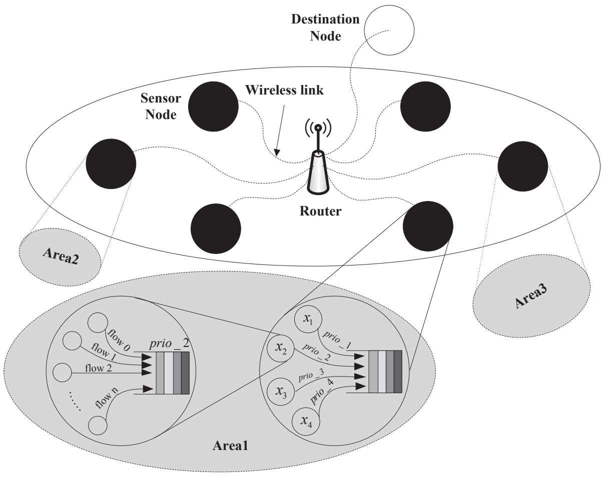


Fig. 1. Network topology

PERFORMANCE ASSESSMENT

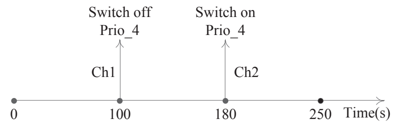
A. Experiment environment and setting

In order to evaluate the performance of the proposed Bio-RC approach for WMSN, simulation studies are used to evaluate the performance in terms of graceful performance degradation, self-adaptivity, scalability and service differentiation. In addition, evaluation studies investigate how parameters affect the performance of the Bio-RC approach in terms of stability and convergence and provide effective parameter setting on the basis of congestion-oriented metrics. The simulation experiments are conducted in a wireless sensor network, the traffic flows are transmitted by wireless medium through a Router to the Destination Node (DN) as shown in Fig. 1. The time interval between two successive evaluations of sending rate of data flow initiated by Sensor Node (SN) is set to 1 second.

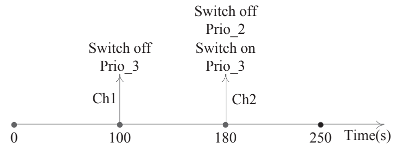
The parameters setting of the proposed Bio-RC model shown in Equation (4) are set up as follows: $A = \frac{r}{N} \cdot \begin{bmatrix} 3 & 1.7 & 1.4 & 1.2 \\ 1.7 & 3 & 1.3 & 1.1 \\ 1.4 & 1.3 & 3 & 1.1 \\ 1.2 & 1.1 & 1.1 & 3 \end{bmatrix}$, $r = 1$, $N = 1024$, where N means the maximum available bandwidth of the network, i.e. 1Mbps. As discussed above, the rate of each traffic flow converges to a global stable EP when all the eigenvalues of matrix A are positive.

B. Stability analysis under different traffic loads

Two random network scenarios (Test1 and Test2) with two changes, such as removing or injecting data flows, are used to evaluate the performance of the proposed approach, such as the stability, scalability and adaptivity. Each scenario with a random initial rate of traffic flows has two changing network states, change1 (Ch1) and change2 (Ch2), as shown in Fig.2 and three global stable states (stable, stable1 and stable2) as shown in Table I. In Test I, we switch off the flow Prio_4 at $t = 100s$, and then switch on it again at $t = 180s$. While in Test2, we switch off the flow Prio_3 at $t = 100s$, and then switch on it again and switch off the flow Prio_2 at $t = 180s$. Individual element in Table I is the data flow rate. Moreover, we assume that all data flows have the same characteristics of the growth rate r, the intra-specific competition coefficient β and the maximum capacity N of each data flow. However, the inter-specific competition coefficient between any two flows are various among them, such as the inter-specific competition coefficient of flows Prio_1 and Prio_2 is $a_{12} = 1.7$, while the inter-specific competition coefficient of flows Prio_1 and Prio_3 is $a_{13} = 1.4$.



(a)Test 1



(b)Test 2

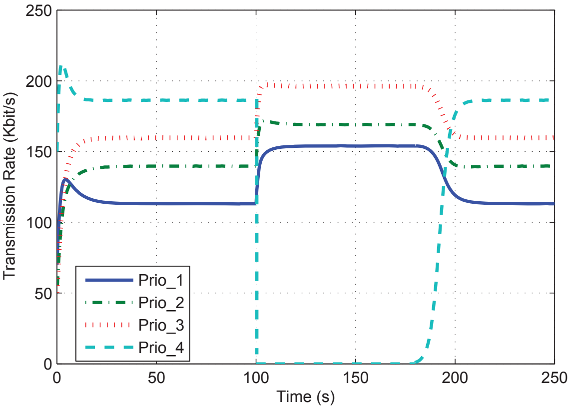
Fig. 2. Removing and/or injecting traffic flow

TABLE I: The EP of the proposed mechanism under different network conditions

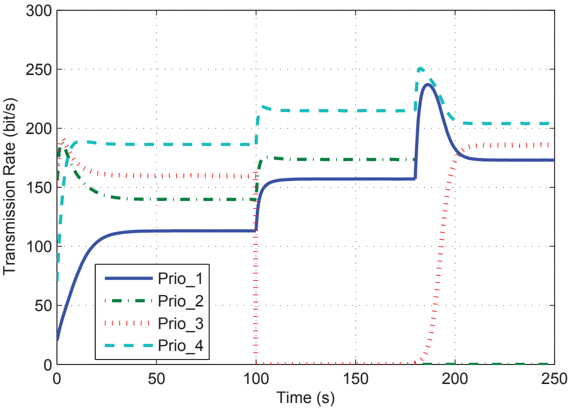
Test	Priority	Initial	Stable	Stable1	Stable2
		0s	100s	180s	250s
Test1	Prio_1	70.0	113.1	154.0	113.1
	Prio_2	50.0	139.7	169.1	139.7
	Prio_3	50.0	159.7	196.2	159.7
	Prio_4	150.0	186.3	0.0	186.3
Test2	Prio_1	20.0	113.1	157.1	173.0
	Prio_2	150.0	139.7	173.6	0.0
	Prio_3	150.0	159.7	0.0	185.8
	Prio_4	70.0	186.3	214.9	204.0

As observed in Table I, the experiments of Test1 and Test2 have the same values of stable EP, which illustrates the proposed approach having one stable EP under an arbitrary nonnegative initial value. The point (113.1,139.7,159.7,186.3) is the global stable EP for all flows co-existing in the bandwidth-limited WMSN. When the flow Prio_4 becomes extinct at $t = 100s$ for some unknown reasons in Test1, the other data flows will soon adaptively reach another new EP (154.0, 169.0, 196.2, 0.0). At the instant $t = 180s$, the flow Prio_4 is injected into the network again, then the system returns back to the original EP. Similarly, Test2 also shows the excellent performance of the Bio-RC approach in terms of adaptivity, scalability and stability. When the flow Prio_3 is switched off at $t = 100s$, other categories of flows will reach a new stable EP (157.1, 173.6, 0.0, 214.9), and then the WMSN will reach another new stable EP (173.0, 0.0, 185.8, 204.0) after switching off the flow Prio_2 and switching on the flow Prio_3 at $t = 180s$ in Test2.

Fig. 3 takes a close look at the behavior of all traffic flows with differentiated priority under the changing network load. We aim to reveal the process of the system keeping stable after changes are introduced into the network. As can be seen, when the data flow is changed for some reasons (i.e., some flows are injected or removed), the system can re-converge to a new stable EP quickly for its characteristic of self-adaptivity. And the convergence time is very short (about twenty iterations) for each violation of the stable condition as shown in Fig. 3(b) at $t = 100s$ and $t = 180s$. Moreover, the proposed Bio-RC approach provides smooth transmission rates for all the traffic flows, which also assists in avoiding or reducing the possibility of buffer overflow and network congestion. When some high priority emergency data streams are injected into the network as shown in Fig. 3, the proposed mechanism can also achieve graceful performance degradation.



(a)Test 1



(b)Test 2

Fig. 3. Transmission rates

C. Parameter setting and analysis

In this section, the impact of parameters β, r on a realistic network environment is investigated. Each scenario, concerning different combinations of β, r values, is executed 10 times and the average values of metrics over all scenarios are presented below.

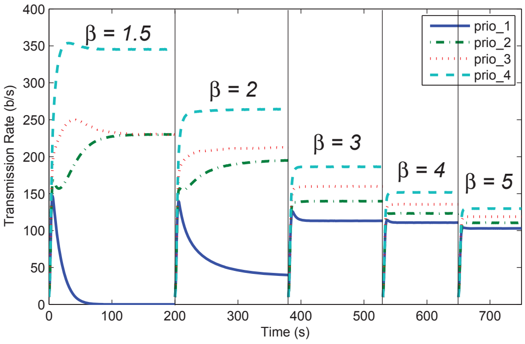
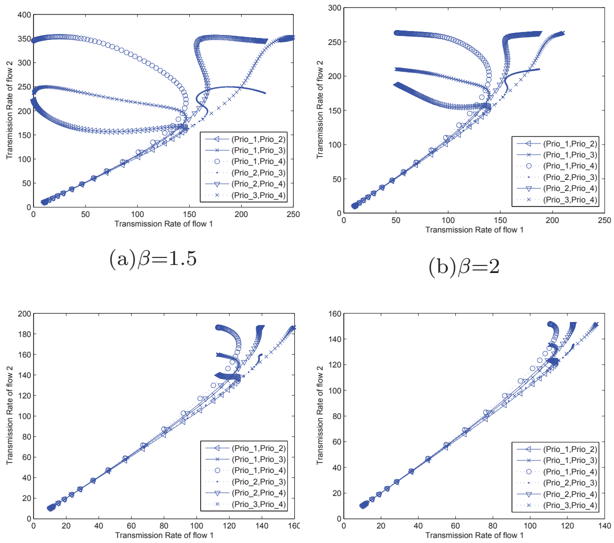


Fig. 4. The equilibrium point with different β values

When β increases from 1.5 to 5 as shown in Fig. 4, the sending rates of all data flows become less differentiated, and the remaining difference in data flow rate is mainly caused by the different inter-specific competition coefficients. With the increment of value β, i.e. the competitive effect of flow j on the sending rate of flow i is much less than that from the inside of flow i, the total sending rate of all data flow is found being decreased. Even though there is no upper bound for β value, it is worth pointing out that as β increases, the EP value decreases and the received data rate at the DN may be reduced.

The phase plane of the scenarios with different values of β as shown in Fig. 5 illustrates the stability, rapid convergence and differentiation of transmission rates of two data flows with all the combinations of priorities. As observed in Fig. 5(c) when $\beta = 3$, the sending rate of each flow can converge to the global stable point without any fluctuations. Moreover, with the increment of intra-specific competition coefficient β, the phase plane inclines to a small region (the EP), which means that there is less difference among four priorities. However, when the value of intra-specific competition coefficient is equal to 1.5 (i.e. the inequality $a_{ij} < \beta$ is not satisfied, for $a_{12} = 1.7$), the network system is not stable as shown in Fig.5(a), which can be effectively avoided from proper parameter settings.

In all the previous scenarios, the parameter r for each flow is set to 1. Further simulation studies are carried out to study the influence of r on stability. Results show that the stability of all traffic flows is independent on r, i.e. the stable EP (113.1, 139.7, 159.7, 186.3) is constant for any flow growth rate as shown in Fig. 6. This implies the stable equilibrium state x_i^* for flow i keeps its sending rate unchanged whatever its initial growth rate r_i increases to. Analytical evaluations from the comparisons in Fig. 6 suggest that high values of r can contribute to fast convergence to the stable equilibrium solution.



(a)β=1.5 (b)β=2

(c)β=3 (d)β=4

Fig. 5. Phase plane of two species

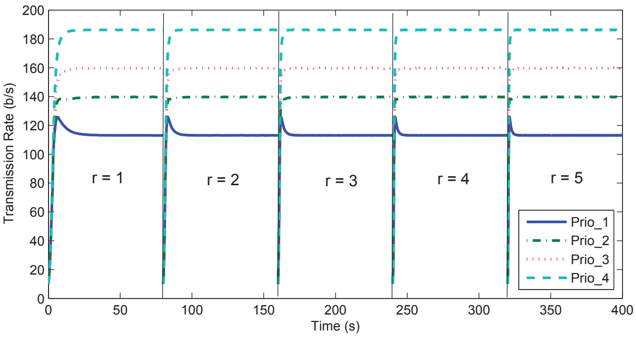


Fig. 6. Transmission rate under different r values

CONCLUSIONS

In this paper, we propose a novel bio-inspired rate control (Bio-RC) approach to meet the differentiated QoS requirements for various applications in WMSN. Based on the extended competitive LV model, the Bio-RC model considers the effect of injected bursty data flows on the system stability as well as the limited network resources and competitions from other data flows. It is proven that Bio-RC approach has a global stable EP and can fast re-converge to a new EP under changing network conditions, while keeping all data flows co-existing and serviced with differentiated QoS. The source traffic rates can be adjusted optimally according to the value of EP. From the analysis of simulation results, we illustrate how the variations of the approach's parameters influence stability, scalability and distinction of traffic flows. Performance evaluations suggest certain values for parameters a_{ij}, β_i and r that are able to achieve low packet loss probability and guarantee bandwidth for real time traffic with a higher priority .

APPENDIX

According to the ordinary differential equation, the Equation (4) can be rewritten for data flow i as:

$$\frac{dx_i(t)}{dt}\cdot\frac{1}{r\cdot x_i^2(t)}=\frac{N-\sum\limits_{j=1,j\neq i}^{n}a_{ij}x_j(t)}{Nx_i(t)}-\frac{\beta}{N}$$

$$-\frac{1}{r}\cdot\frac{d\left(\frac{1}{x_i(t)}\right)}{dt}=\frac{w(t)}{Nx_i(t)}-\frac{\beta}{N},\quad w(t)=N-\sum_{j=1,j\neq i}^{n}\alpha_{ij}x_j(t)$$

We define: $y(t)=\frac{1}{x_i(t)}$, then the above equation can be written as:

$$\frac{dy(t)}{dt}+\frac{w(t)\cdot r}{N}\cdot y(t)=\frac{\beta\cdot r}{N}$$

$$y(t)=e^{-\frac{w(t)r}{N}\cdot t}\cdot\left(\int\frac{\beta r}{N}\cdot e^{\frac{w(t)r}{N}\cdot t}dt+C\right)$$

Define: $t=0$,then $C=\frac{1}{x_i(0)}$.

$$e^{-\frac{w(t)r}{N}\cdot t}\cdot\left[\frac{\beta}{w(t)}\cdot\left(e^{\frac{w(t)r}{N}\cdot t}-1\right)+\frac{1}{x_i(0)}\right]=\frac{1}{x_i\,(t)}$$

$$x_i\,(t)=\frac{w(t)\cdot x_i\,(0)}{\beta x_i\,(0)+[w(t)-\beta x_i\,(0)]\cdot e^{-\frac{w(t)r}{N}t}}$$

then we can obtain Equation (5).

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