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Extended Formulation of TCP Vegas Inspired by a Controller Structure of Cell Cycle Pathway Networks

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細胞周期・パスウェイ・ネットワークの制御器による TCP Vegasの拡張定式化

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Abstract An extended form of the Transmission Control Protocol (TCP) inspired by signal transduction networks of cell cycle is formulated where TCP Vegas is selected as a reference for the TCP dynamics.

概要　本稿では、細胞周期のシグナル伝達ネットワークからのヒントによって、拡張されたTCP Vegasを定式化される、ここでTCP VegasはTCPダイナミックスのための参照として選択される。

1. Introduction

The molecular signaling mechanism of cell cycles in yeast shows dynamic features on cyclin signals, where the period of signaling is robust to variations of parameters of the corresponding pathway networks [1,2]. The cyclin and related molecules in the cell cycle of yeast are important for sustaining the cell reproduction process. From modeling and simulation of the signal transduction network [3,4,5] of yeast cells, we can get a better understanding of the biological function of cells. Further, the aspects of the cellular signaling mechanism from the viewpoint of informatics can be a hint for us to study and enhance not only existing information network protocols, but also even those for communication networks in the near future.

With the recently growing interest in exploring the dynamics of biologically-inspired networking [6], we notice that there is a striking resemblance between the cyclin-centered cellular signaling process and the temporal process of the *congestion (control) window* size (cwnd) in TCP [7,8]. A generalized formulation of TCP was presented in [7,8], which was inspired by the dynamics of signal transduction networks of cell cycle in yeast. In this report, we discuss an extended TCP mechanism under the condition that two variables of the corresponding cellular signaling process are extracted, which is the combination of TCP Vegas and an additional dynamics on the congestion window.

2. A Pathway-Inspired TCP Model

Based on our previous discussions in [7,8], we set the variables of the cell cycle dynamics model as *Cln2* and *Clb5*, which are embedded in a feedback controller structure. By modeling the dynamics of this pathway network that takes a form of a cascade with feedbacks, we can formulate a controller in terms of informatics. The corresponding controller structure is given in Fig.1.

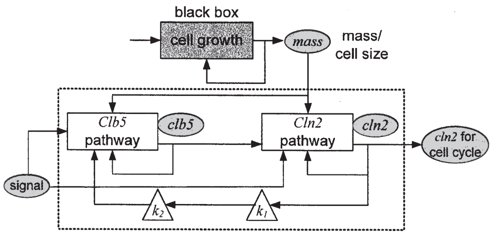

Figure 1: The controller structure for the signal transduction network that consists of *Cln2* and *Clb5* with feedbacks

Let *Cln2* be the metaphor for the congestion (control) window size $w_i(t)$ and *Clb5* represents $1/D_i(t) = D_i^*(t)$, where $D_i^*(t)$ refers to the *round trip time* (RTT) including the propagation delay.

Let us consider the following Master equation

$$\frac{d}{dt} w_i(t) = \kappa_i(t)\left(1 - \frac{q_i(t)}{u_i(t)}\right) + \varphi_i(t) \quad (1)$$

which is an extension of the generalized version of the TCP window size equation given in [9] by Wei *et al.* in the form of

$$\frac{d}{dt} w_i(t) = \kappa_i(t)\left(1 - \frac{q_i(t)}{u_i(t)}\right). \quad (2)$$

It can be seen that Eqns. (1) and (2) are similar except for the feedback factor $\varphi_i(t)$ which corresponds to the extended form of our proposed TCP dynamics.

We set $q_i(t) = k_q$ as constant and replace $D_s^*(t)$ by $T_i(t)$ to obtain $u_i(t)$.

$$u_i(t) = \frac{k_1}{\sum_{l_1} k_{01}\, w_i(t)^{l_1} + \sum_{l_2} k_{02}\, q_i(t)^{l_2} + \sum_{l_3} k_{03}\, T_i(t)^{l_3}}$$

Then we also define

$$\varphi_i(t) = \frac{k_2\, k_G\, \exp(\mu\, t)\, \zeta_i(t)}{\sum_{m_1} k_{21} w_i(t)^{m_1} + \sum_{m_3} k_{23} D_s^*(t)^{m_3}}$$

with

$$\zeta_i(t)=\left(\frac{k_3}{\sum_{z_1} k_{31} w_i(t)^{m_1}+\sum_{z_3} k_{33} D_s^*(t)^{m_3}}\right)^{-1}.$$

Let $\mathrm{sgn}(\cdot)$ take the form of a sign function, then the discrete formulation (quantization) becomes

$$\frac{d}{dt}w_i(t)=D_s^*(t)\,\mathrm{sgn}\left(\kappa_i(t)\left(1-\frac{q_i(t)}{u_i(t)}\right)+\varphi_i(t)\right)$$

where $\kappa_i(t)$ refers to the discrete form of the mass function in a triangular shape monotonically increasing from 0 to 1 and decreasing from 1 to 0.

The term $(1-q_i(t)/u_i(t))$ can be related to the term $\left(\frac{1}{d_s}-\frac{1}{D_i(t)}\right)w_i(t)$ in TCP Vegas.

3. Stability Analysis of TCP Dynamics: Free of Any Transformation

As Wei *et al.* inferred [9] the stability of TCP Vegas is studied by analyzing the TCP transmission processes by using the Laplace transformation. The congestion (control) window size is normally used for the packet model, but it is not so easy to carry out a theoretical analysis of TCP Vegas directly on the packet form in existing methods of optimization theory. What captures our attention is whether or not a method of stability analysis exists without any transformation (e.g. Laplace transformation) in terms of automatic control theory.

Based on the above-mentioned inference, it is obvious that the stability of the extended TCP Vegas proposed above equals to the problem of the analysis of the summation of TPC Vegas and $\varphi_i(t)$, i.e.,

$$\text{Extended TCP dynamics} = \text{TPC Vegas} + \varphi_i(t)$$

where

$$\varphi_i(t)=g_{w_1}(W_i(t))+\frac{g_{D_2}(D_s^*(t))}{g_{w_1}(W_i(t))+g_{D_2}(D_s^*(t))}$$

and $g_{w_1}(\cdot)$, $g_{D_2}(\cdot)$ are polynomial functions on the variables, respectively.

There, the item $\varphi_i(t)$ is the object for stability analysis and controller synthesis. By observation where the denominator $g_{w_1}(W_i(t))+g_{D_2}(D_s^*(t))$ becomes zero, we can calculate the solution to the stability. The item of $g_{w_1}(W_i(t))+g_{D_2}(D_s^*(t))$ is the reason for designing the structure of the robust controller with selection of the corresponding parameters of the polynomial functions. This gives rise to richer dynamical features on the TCP control mechanism with a controller structure as illustrated in Fig. 2.

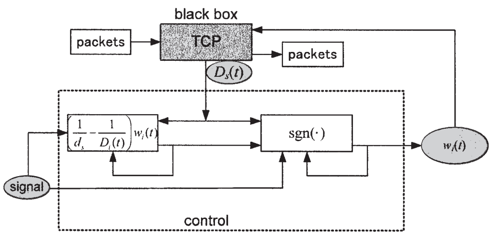

Figure 2: Proposed controller structure of TCP Vegas

4. Conclusion

By designing a discrete form of a controller of a two-variable pathway network of yeast, we obtain an extended TCP dynamics whose stability can be analyzed freely of any transformation.

Here, the channel is assigned proportionally with the load according to their utility/capacity under the fairness of packet transmission; the congestion control strategies are designed to obtain equilibriums of TCP dynamics – the steady states – that affords the stable transition process leading to the robustness under the condition that delay, loss and throughput are treated as random variables. Such an approach provides us a direct observational way to understand the dynamic features of the congestion window control in TCP in order to design a more fair and robust control mechanism, which is expected to help us to improve the performance of signal transmission by TCP.

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