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On Design, Measurement Tools and Robust Control of Wireless Telecommunication Networks

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Preliminary communication

Over the years a lot of rigorous mathematical analysis has been done by systems and controls community for the optimization of multivariable systems with a mathematically rigorous systems theoretic approach. In parallel, wireless telecommunication industry was working on performance measurement analysis tools achieving demonstrable optimization. This paper will elaborate on the need for finding common grounds these two approaches. Some existing measurement tools are also presented.

Decision on measurement tools in design of telecommunications networks implies tradeoffs between reliability, capacity, and the economics in meeting customer demands. The paper first identifies the parameters which can and should be measured to facilitate the optimization for performance of telecommunication networks. Secondly, there are given available resources on measurements tools for these parameters together with a comparative analysis. Thirdly, the hardware setup for some of these measurements will be explained. Finally, a method to find the robust controller for wireless network is introduced.

Key words: H_∞ Control, Wireless Networks.

1 INTRODUCTION

In the recent past, there have been many technological developments in telecommunication networks and the optimization [6]. Data applications are expected to be the primary drivers for deployment of third generation (3G) wireless systems. Performance of Data applications over a CDMA air interface is given in [7]. TCP/IP has been widely used in computer networks for many years. It has also been recommended as a major protocol suit for asynchronous data and data and fax communications. Performance evaluation of TCP/RLP protocol stack over CDMA wireless link is discussed in [1]. The popularity of network-based control systems is continuously growing. To a large extent the actual quality of control in such systems depends on network timing issues such as delay and delay jitter. A seminal work by Soucek and Sauter [3] discussed quality of service concerns in IP based control systems. Wireless control systems can have a huge impact in future development of integrated control systems in decentralized plants, such as refineries, chemical foundries, and hydro power plants. Replacing the wired connections with wireless systems would immensely simplify the amount of work and material involved in maintenance, and, providing that network functions properly, may also enhance the control performance.

It is clear that the evaluating the performance of a networked system is very important and that necessitates the need for choosing a good testing and measurement tool. Also there are huge benefits in correlating performance optimization of networked systems to the optimal control developed by systems and controls community. This paper aims at bringing both together.

This paper is organized as follows. In Section 2 a description of Quality of Service in Telecommunication networks is given where delay and jitter measurements for an IP based network are explained along with the hardware setup description. Power control is an important factor to achieve higher communication link quality and better system capacity. Section 3 poses CDMA power control within a system theoretic H- Infinity framework. Conclusions are given in Section 4.

2 PERFOMANCE OF WIRELESS NETWORKS

Quality of services is a major issue for telecom providers. There is a conflict of interest in what customer desires and what he/she is willing to pay. Growing competition within telecommunication operators and the increase in the expectations of the customers necessitate the operators to keep improvising the network. Also, the demand for the calls and bandwidth capacity is time variant. So the installed capacity is to have a guaranteed availability probability, the Quality of Service.

Below we are explaining which parameters are relevant to most systems in deciding on the performance of the systems.

2.1 End to End Delay

End-to-end delay refers to the time taken for a packet to be transmitted across a network from source to destination. It is explained in RFC 2326 Real time streaming protocol.

2.2 Delay Jitter

The delay jitter (RFC 1889 RTP) is an estimate of the statistical variance of the RTP data packet interarrival time, measured in timestamp units and expressed as an unsigned integer. The interarrival jitter J is defined to be the mean deviation (smoothed absolute value) of the difference D in packet spacing at the receiver compared to the sender for a pair of packets. As shown in (1) below, this is equivalent to the difference in the »relative transit time« for the two packets; the relative transit time is the difference between a packet's RTP timestamp and the receiver's clock at the time of arrival, measured in the same units.

Defining S_i as the RTP timestamp from packet i. R_i as the time of arrival in RTP timestamp units for packet i, then for two packets i and j, D may be expressed as

$$D(i,j)=\left(R_j-R_i\right)-\left(S_j-S_i\right)= \\ =\left(R_j-S_j\right)-\left(R_i-S_i\right) \qquad (1)$$

The interarrival jitter is calculated continuously as each data packet i is received from source SSRC_n, using the difference D for that packet and the previous packet $i-1$ in order of arrival (not necessarily in sequence), according to the formula

$$J=\frac{J+\left(\left|D(i-1,i)\right|-J\right)}{16} \qquad (2)$$

Whenever a reception report is issued, the current value of J is sampled. The jitter calculation is prescribed allow profile-independent monitors to make valid interpretations of reports coming from different implementations.

2.2.1 Delay Jitter Measurement in an IP based Network System

This section compares two available tools for delay jitter measurement in an IP based network.

IPERF: Iperf is a tool to measure maximum TCP bandwidth, allowing the tuning of various parameters and UDP characteristics. Iperf reports bandwidth, delay jitter, datagram loss. Features include running Iperf in bidirectional mode, removed STDLIB requirement for Iperf, and Client reporting of server side statistics in UDP tests. A hardware setup for a satellite based communication system is explained below in Figure 1.

CISCO TOOLS: Delay and jitter can be measured by deploying Cisco routers 17xx or higher with Cisco IOS software code version 12.05T or higher, and configuring the Cisco IOS SAA features. The routers should be placed in the networks next to hosts. This provides statistics for end-to-end connections. Since it is not practical to measure every possible voice path in the network, probes are placed in typical host locations providing for a statistical sampling of typical voice paths. Some examples include a local site-to-site path, a local site-to-remote site path via a 384 kbs Frame Relay circuit, a local site-to-remote site via an ATM permanent virtual circuit (PVC). Figure 2 below describes the setup.

2.3 Throughput

The throughput defines how many bits per unit time can be transferred over a given network path. In an end-to-end view, the delay can be seen as a direct function of the instantaneous throughput. The practical notion of throughput, however, implicitly includes a certain time interval.

The throughput θ can be defined as

$$\theta=\frac{A(t+\Delta t)-A(t)}{\Delta t} \qquad (3)$$

where $A(t)$ denote the aggregate amount of transferred data up to time t.

2.4 Power Control

CDMA is interference limited multiple access system. Because all users transmit on the same fre-

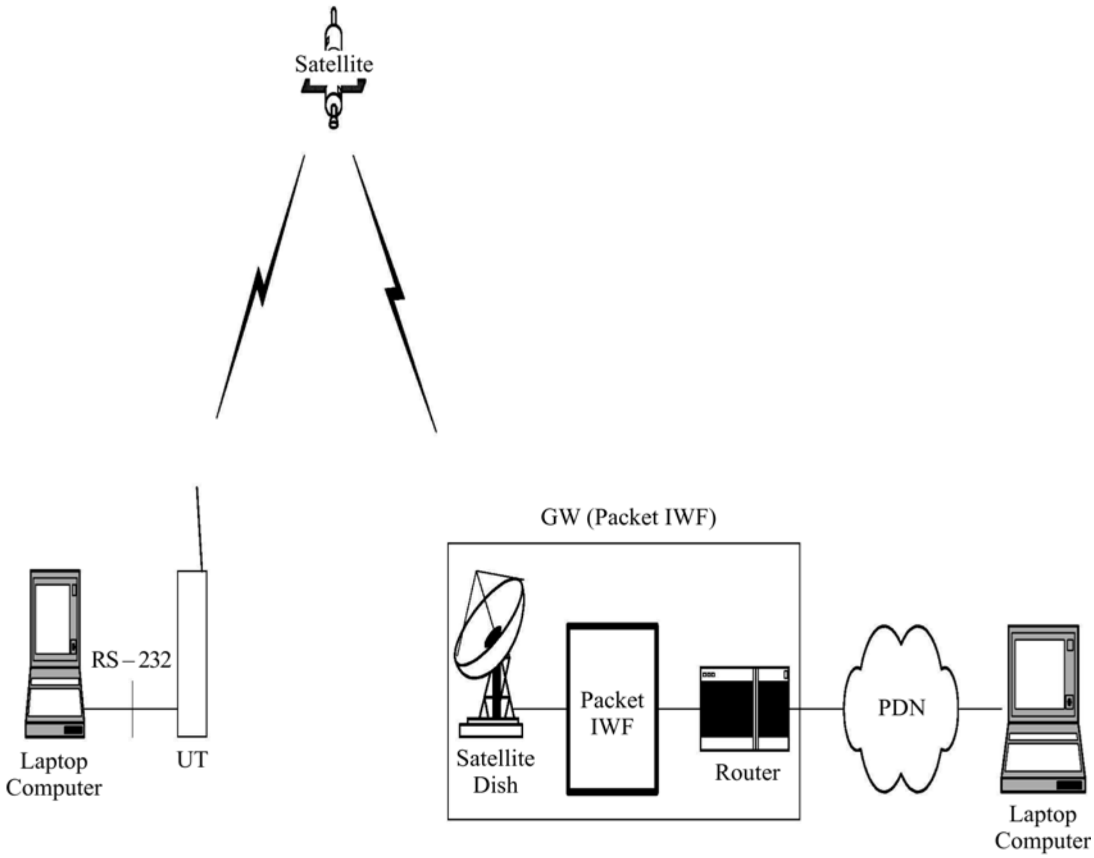

Fig. 1 System Setup for Delay-Jitter measurement with IPERF

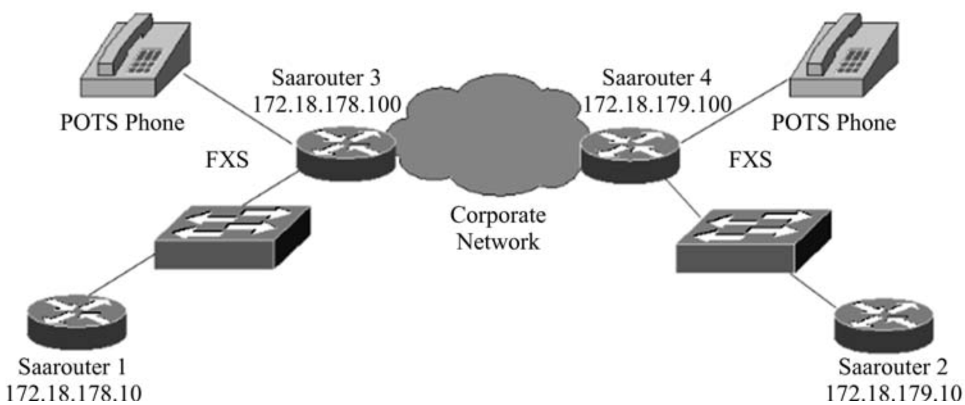

Fig. 2 Set up with Cisco Tools

quency, internal interference generated by the system is the most significant factor in determining system capacity and call quality. The transmit power for each user must be reduced to limit interference, however, the power should be enough to maintain the required Eb/No (signal to noise ratio) for a satisfactory call quality. Maximum capacity is achieved when Eb/No of every user is at the minimum level needed for the acceptable channel performance. As the Mobile Station moves around, the RF environment continuously changes due to fast and slow fading, external interference, shadowing, and other factors. The aim of the dynamic power control is to limit transmitted power on both the links while maintaining link quality under all conditions.

3 CDMA POWER CONTROL WITHIN A SYSTEM THEORETIC H-INFINITY FRAMEWORK

Primary aim of this section is to give an overview of how to pose CDMA power control within a frame of control systems theory [5].

Spectrum efficiency is one of the biggest positive outcomes of Code Division Multiple Access. It is possible because in this technique, all users operate on the same channel. As described in the section II good power control facilitates higher communication link quality and better system capacity. In order to track the desired signal-to-interference-plus noise ratio (SINR) under round trip delay, multiple access interference, channel fading, and noise, a time delay based state space model described below is presented in [8]. The model represents the tracking error dynamics.

3.1 Problem Formulation

Measurement SINR at the base station can be written as

$$y_k = x_k + f_k - w_k \tag{4}$$

Here x_k is the transmission power, and f_k is the fading gain. The overall interferences that includes quantization error, Multiple Access Interference, Additive White Gaussian Noise, and nonlinear effect due to transmission power limitation are describes as w_k.

Defining the sum of downlink, uplink, and overall delay respectively as d_1, d_2, and d, such that $d=d_1+d_2$, transmission power x_k can be denoted as

$$x_k = x_{k-1} + u_{k-d} \tag{5}$$

Here u_k is the power control update command. It is desired to keep the SINR at a set point namely a desired value defined as r_k. Target SINR is specified jointly by the frame error rate (FER) statistics and the SINR error statistics in the outer loop for power control. Tracking error than can be formulated as

$$e_k = r_k + y_k \tag{6}$$

Working with (4), (5) and in (6) will yield

$$e_k = e_{k-1} - u_{k-d} + \delta_{k-1} \tag{7}$$

where $\delta_{k-1}=w_k-w_{k-1}-f_k+f_{k-1}+r_k-r_{k-1}$ indicates the uncertain interference, fading noise, and nonlinear effects. The state vector X_k can now be defined as

$$X_k = \begin{bmatrix} e_k \\ u_{k-d} \\ . \\ . \\ . \\ . \\ u_{k-2} \\ u_{k-1} \end{bmatrix} \tag{8}$$

The past power control update commands u_{k-1} to u_{k-d} are considered in the state vector.

Tracking error dynamic equation is expressed as

$$\begin{aligned} X_{k+1} &= AX_k + Bu_k + D\delta_k \\ e_k &= CX_k \end{aligned} \tag{9}$$

where

$$A = \begin{bmatrix} 1 & 0 & -1 & \dots & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \dots \\ \dots \\ \dots \\ 1 \end{bmatrix}, \; C = \begin{bmatrix} 1 \\ 0 \\ \dots \\ \dots \\ \dots \\ 0 \end{bmatrix}^T, \; D = \begin{bmatrix} 1 \\ 0 \\ \dots \\ \dots \\ \dots \\ 0 \end{bmatrix}$$

In the tracking error dynamic equation in (9), the power tracking design purpose is to specify control u_k such that e_k is minimum under the influence of the signal δ_k. Note that δ_k is highly uncertain due to interference, fading, noise and nonlinear effects. For the state space model (9), the pair (A, B) is controllable.

In the state-space model (10), a state feedback controller can be introduced such that

$$u_k = KX_k \tag{10}$$

The closed-loop state-space system consisting of (9) and (10) can be written as

$$X_{k+1} = (A + BK)X_k + D\delta_k$$
$$e_k = CX_k \qquad (11)$$

Now we can solve the H-Infinity tracking problem as

$$\frac{\frac{1}{k_f}\sum_{k=0}^{k_f} e_k^T R_1 e_k}{\frac{1}{k_f}\sum_{k=0}^{k_f} \delta_k^T R_2 \delta_k} < \gamma^2 \qquad (12)$$

Based on the robust power control scheme, we want to design a state feedback control such that the power gain from δ_k to e_k is minimum. In Equation (12) R_1 and R_2 are two positive weighting factors for the designer, and is k_f the total transmission data length [8]. Here γ^2 is the ratio of the weighted average power of tracking error e_k over that of the disturbance δ_k. The weighted ratio should be less than γ^2 from the power perspective. In the next section is represented the theoretical framework that could could towards finding a solution to the control problem established in this section.

3.2 Exploring Bounded Real Lemma

The work by de Souza and Xie [2] deals with the Discrete-time Bounded Real Lemma and its application in the characterization of all static state feedback H-Infinity Controllers for discrete time systems. In this section we are elaborating on the Bunded Real Lemma with a suggested technique to explore the possibility of parameterizing CDMA H-Infinity Power Controllers. As generalized using Equation (9) the results can be given in terms of either the positive semi-definite strong solution, or the positive semi-definite stabilizing solution of a discrete algebraic Riccati equation.

Notations and Definitions: Throughout this section the notation $M \geq N$ ($M > N$) with M and N being symmetric matrices, means that the matrix $M - N$ is positive semi-definite (positive definite). $\| G(z) \|_\infty$ will refers to the infinity norm of a stable discrete-time transfer matrix $G(z) \cdot | G(z) \|_\infty = = suo_{0 \leq \omega \leq 2\pi} \sigma_{\max}[G(e^{j\omega})]$, where $\sigma_{\max}(\cdot)$ stands for the maximum singular value of a matrix.

Consider the discrete algebraic Riccati Equation

$$A^T PA - P + \left(A^T PB + M^T\right)\left(R - B^T PB\right)^{-1}\left(B^T PA + M\right) + Q = 0 \qquad (13)$$

where A, B, Q, R and M are real matrices of dimensions $n \times n$, $n \times m$, $n \times n$, $m \times m$ and $m \times n$ respectively, and with Q and R being symmetric matrices. A real symmetric matrix P is said to be a stabilizing solution to (13) if P satisfies (13) and the matrix $\overline{A} = A + (R - B^T PB)^{-1}(B^T PA + M) + Q = 0$ stable. In the case when all of the eigenvalues of $\overline{A}$ lie in the closed unit disk, P is said to be a strong solution to (13).

Let G(z) be a p × m real rational transfer function matrix of a proper linear discrete-time system and consider a state-space realization (A, B, C, D_{sys}) of G(z), i.e. with no feed forward matrix i.e. $D_{sys} = 0$,

$$G(z) = C(zI - A)^{-1} B \qquad (14)$$

Note that no a priori assumption on minimality of the realization (A, B, C, D_{sys}) is made. A bound for the H-Infinity norm of G(z) is provided by the following version of the Discrete-time Bounded Real Lemma.

Lemma 1: The following statements a) and b) are equivelent

a) A is a stable matrix and $\| C(zI - A)^{-1} B \|_\infty \leq \gamma$.

b) (C, A) has no observable modes on the inner circle, and there exists a strong positive definite symmetric solution to the Riccati equation.

$$\begin{pmatrix} A^T PA \\ -P \end{pmatrix} - \gamma^2 \begin{pmatrix} A^T PA \\ +C^T D \end{pmatrix} \cdot \cdot \begin{bmatrix} I \\ -\gamma^{-2}\left(B^T PB\right) \end{bmatrix}^{-1} (PBA) + C^T C = 0 \qquad (15)$$

such that $[I - \gamma^{-2}(B^T PB)] > 0$.

Lemma 2: The following statements a) and b) are equivelent

a) A is a stable matrix and $\| C(zI - A)^{-1} B \|_\infty \leq \gamma$.

b) There exists a matrix $\hat{P} = \hat{P}^T > 0$ satisfying

$$\begin{pmatrix} A^T \hat{P} A \\ -\hat{P} \end{pmatrix} - \gamma^2 \left(A^T \hat{P} B\right) \cdot \cdot \begin{bmatrix} I \\ -\gamma^2\left(B^T \hat{P} B\right) \end{bmatrix}^{-1} \left(B^T \hat{P} A\right) + C^T C < 0 \qquad (16)$$

such that $[I-\gamma^{-2}(B^T\hat{P}B)]>0$.

c) There exists a stabilizing solution $P=P^T>0$ to the Riccati Equation

$$\begin{pmatrix} A^T PA \\ -P \end{pmatrix} - \gamma^2 \left(A^T PB\right) \cdot$$

$$\cdot \begin{bmatrix} I \\ -\gamma^{-2}\left(B^T PB\right) \end{bmatrix}^{-1} \left(B^T PA\right) + C^T C = 0$$

such that $[I-\gamma^{-2}(B^TPB)]>0$. Moreover, $P<\hat{P}$.

It is to be emphasized that unlike system and theory approach where effects of disturbance in the output are aimed to be eliminated to the maximum possible, in CDMA power control signal to noise ratio is not maximized. It is important to track the signal to noise ratio at a designer defined level.

Main aim of this section was to give an example of a wireless communication problem being posed in an H-Infinity system theoretic framework and hence system theoretic optimal control tools can be used [9]. This is an active area of the current research. This paper is focusing on introducing the problem and finding the common grounds between telecommunication measurements, performance optimization and systems theoretic optimal control.

4 CONCLUSIONS

Telecommunication technology is expected to be the primary driver over the next few decades. With ever increasing demand it is imperative to find common grounds between theoretical achievements in other fields in order to improve. Test and measurement setups play a big role in improving the performance of a network and the IP based equipment used by the consumer. This paper stresses the need for correlating test, measurement, optimization, and performance for telecommunication networks using the control theoretic knowledge. This paper also explains some measurement variables and exemplifies a telecommunication performance problem in a system theoretic framework.

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O projektiranju, mjerenjima i robusnoj regulaciji u bežičnim telekomunikacijskim mrežama. Kroz godine je mnogo postignuto u optimizaciji multivarijabilnih sustava kroz rigorozan matematički teoretski pristup. U isto vijeme, u bežičnoj telekomunikacijskoj industriji radilo se na metodama za mjerenje i analizu kako se moglo optimirati rad telekomunikacijske mreže. Glavna tema ovog rada je uvod u analizu koja povezuje teoriju regulacijskih sustava i optimiranje rada bežičnih telekomunikacijskih mreža. Neke postojeće mjerne metode su također objašnjene.

Izbor mjernih metoda i mjerenja potrebnih za uspostavljanje optimalne i pouzdane bežične telekomunikacijske mreže uključuje uspostavljanje ravnoteže između pouzdanosti, kapaciteta i cijene u zadovoljavanju trenutnih i budućih potreba korisnika. Uspostavljanje i održavanje efikasne bežične telekomunikacijske mreže je svakodnevni izazov. Ovaj rad prvo identificira parametre koji mogu i trebaju biti mjereni kako bi se omogućilo optimiranje rada mreže. Zatim je data kratka analiza opreme za mjerenje uz objašnjenje hardwera za takva mjerenja. Na kraju je dana struktura robusnog regulatora za bežične telekomunikacijske mreže.

Ključne riječi: bežične mreže, H_∞ regulacija

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