On the use of one bit quantizers in networked control

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**Abstract**

This paper addresses the following problem in networked control: “If a control law is implemented over a channel that supports a certain fixed bit rate what is the best choice for the control update rate and, consequently, the number of bits carried in each sample?” A restricted architecture in which linear filters are used for the encoder/decoder is considered and a quantizer with linear feedback is deployed. Subject to these restrictions, a procedure for designing the controller and associated filters is presented. These filters are then deployed to choose the best number of bits per control update. It is shown, subject to the above restrictions, that it is generally best to use one bit per sample, in which case, the control update rate is equal to the bit rate. Our analysis has two points of departure from contemporary literature in this area. Firstly, we focus on bits per unit time, as opposed to bits per sample. Secondly we use a fixed number of bits in every time period as opposed to an average bit rate.

1. Introduction

Control theory has traditionally ignored communication constraints, but the recent developments in networked control systems, and the problems arising there from, have inspired considerable interest in the interplay between communication and control (Antsaklis & Baillieul, 2004; Wong & Brockett, 1997). A major focus in this literature has been on the effect of network constraints on performance and stability; typical constraints are limits on (average) data rate, random delays and lost packets. There has been important progress in several areas, (see Braslavsky, Middleton, and Freudenberg (2007), Goodwin, Silva, and Quevedo (2010), Lian, Moyne, and Tilbury (2003), Ling and Lemmon (2004), Nair and Evans (2004), Nair, Fagnani, Zampieri, and Evans (2007), Nilsson (1998), Savkin (2006), Schenato, Sinopoli, Franceschetti, Poolla, and Sastry (2007), Seiler and Sengupta (2005) and Tatikonda and Mitter (2004). The current paper adopts an alternative point of view and assumes that the constraint is on the bit rate in the communication channel between control law and plant rather than the sampling rate. There are several ways that the question considered here could be formulated, for example where the constraint on bit rate lies between controller and plant, between plant and controller or both. Here, we explore the first of these options. This choice was motivated, in part, by the practical problem of inner loop power control in WCDMA mobile communications (Cea & Goodwin, 2011; Dahlman, Parkvall, Skold, & Beming, 2007). In this problem, the input update period is set to $\Delta = 0.667$ ms and, in traditional implementations, 1 bit per sample is used. However, it would be possible to maintain the same input bit rate whilst changing the input update period to $p\Delta$ and to use $p$ bits/sample. This change of paradigm raises the question as to whether, or not, the choice $p = 1$, used in practice, is the best choice. Preliminary simulation studies conducted by the present authors suggest that 1 bit/update is actually the best choice. The bit rate is the product of the number of bits per sample and the control update frequency. Since $p$ bits per sample permits $2^p$ quantization levels, a higher value for $p$ reduces the quantization error but also increases the period over which the input must be held, therefore, the ability of the controller to reduce the effect of disturbances. This decomposition of the bit rate into the product of bits per sample and input update frequency results in an obvious trade-off and leads to the question: "What is the best allocation of a given bit rate into the..."
number of bits per sample and the number of control updates per second?" This paper addresses this problem.

A restrictive (pragmatic) view of network control in which linear filters are utilized for the encoder/decoder pair is adopted. The single input single output case is considered, and a quantizer with linear feedback is deployed to assign the signal of interest to the available bits. The analysis is restricted to open loop stable systems. It would be interesting to relax these restrictions. However, these restrictions are used here to simplify the analysis. We leave it for future research to consider other scenarios.

Subject to the above restrictions, a design procedure in which, for each choice of the number of bits in the quantizer, the optimal controller, encoder/decoder and quantizer feedback are chosen. These designs are then used to choose the optimal number of bits/control update. It is shown, surprisingly in our view, that one bit per control update is typically the best choice. Consequently a control update rate equal to the available bit rate is best. This choice corresponds to implementing the control law using a scaled sign function.

2. A class of models

Consider a single input single output linear continuous time system and assume the following:

A.1 The bit rate of the input channel (between controller and plant) is restricted to $B$, bits/s so that $\Delta_1 = 1/B$, $s$ is the smallest possible control update period.

The output is always sampled at period $\Delta_1$ and an appropriate anti-aliasing filter is deployed at this sample period. Filtering at the lower sample period is implicit in the form of the controller. The input is held constant for $p$ samples to allow a $p$ bit quantizer to be used i.e. $p$ bits are used to code the input signal. When the input is up-sampled to period $\Delta_1$, the resulting system can be described, without loss of generality, in innovations form (Anderson & Moore, 1979; Goodwin & Sin, 1984) as follows:

$$x_{k+1} = Ax_k + Bu_k + Ke_k$$

$$y_k = Cx_k + e_k$$

where $x_k \in \mathbb{R}^n$, $u_k \in \mathbb{R}^1$, $y_k \in \mathbb{R}^1$, $e_k \in \mathbb{R}^1$ are the state, plant input, plant output and innovations sequence having variance $\sigma_i$ respectively. Furthermore, assume the transfer function $C(zI - A)^{-1}B$ to have relative degree $d + 1 < n$. Hence, for $d = 0$, $CB \neq 0$ and for $d \geq 1$,

$$CA^IB = 0 \quad \forall i = 0, 1, \ldots, d - 1; \quad CA^IB \neq 0.$$  (3)

Additional assumptions are introduced as follows:

A.2 The discrete time transfer function from $\bar{u}$ to $y$ is stable and minimum phase.

A.3 A uniform-interval-nearest-neighbour quantizer with $2^p$ levels is deployed.

A.4 All bits used in the quantizer are communicated between controller and plant over a serial link supporting $b_i$ bits/s.

A.5 The communication channel is error free.

Note that, a quantizer which allocates $p$ bits/sample introduces a transmission delay of period $\Delta_p = p\Delta_1$.

3. Feedback architecture and quantizer

The proposed architecture for the feedback system is shown in Fig. 1. In this figure, a superscript $p$ denotes either a downsampled signal with period $p\Delta_1$ or a system that operates at period $p\Delta_1$. The architecture shown in Fig. 1 has the following degrees of freedom: $C^p$ (a controller which is driven by a signal with sample period $\Delta_1$, which outputs a control every $p$th sample), $(1 + L_p)$ and $(1 + L_p)^{-1}$ (the channel coder and decoder), $Q^p$ (a $2^p$ level quantizer having step size $\lambda^p$ and $H^p$ (providing feedback around the quantizer). For realizability $L_p$ and $H^p$ are constrained to be strictly proper. We define $s^p = \bar{v}^p + q^p$ where $q^p$ denotes the quantization error sequence. At sample time $k = \ell p$, $\ell \in \mathbb{Z}^+$, the controller has knowledge of all past outputs (sampled at period $\Delta_1$), that is $y_{\ell p}, y_{\ell p-1}, y_{\ell p-2}, \ldots$. The controller then generates an input signal $u^p_k$. This input signal is held for $p$ samples. The up-sampled input signal is denoted as $\bar{u}_k$. Note that $\bar{u}_{\ell p+i} = u^p_i$, $i = 0, 1, \ldots, p - 1$. After filtering by $(1 + L_p)$ the input signal is quantized to $2^p$ levels which leads to a $p$ bit representation. It takes $p\Delta_1$ to transmit these $p$ bits over the communication channel to the plant input thus satisfying the bit rate constraint. The signal is passed through $(1 + L_p)^{-1}$, and the series to parallel conversion is applied followed by D/A conversion. This process produces a piecewise constant control signal constrained to the same $2^p$ levels. This signal is then passed to a $p$ sample hold so that the plant input, $u^p_k$, is constant for $p$ successive samples. During this period, the next $p$ bits are received, allowing the next plant input to be reconstructed, and so on. The total delay between sample time, $k = \ell p$, (the time that a sample of the output is taken) and the first time that the resultant control, $u^p_k$, effects the output of the plant is $(d + p + 1)$ samples. Note that, due to the $p$ sample hold nature of the input, the output at sample period $\Delta_1$ will be cyclostationary with period $p$.

We assume a uniform quantizer, which is characterized by the step size between quantization levels. $Q^p[\cdot]$ denotes the quantization operation. The quantization error is defined as

$$q^p = \bar{v}^p - Q[\bar{v}^p]$$

$$= F^p_{\lambda^p}[\bar{v}^p]$$

Fig. 1. Proposed four degree of freedom architecture ($C^p$, $L^p$, $H^p$ and $Q^p$).
where

\[ F_p^A[x] = \begin{cases} 
  x + (2p + 1)\lambda & \forall x \in (-\infty, -2(2^{p-1} - 1)] \\
  x + (2i - 1)\lambda & \forall x \in (2i - 2, -2(i - 1)] \\
  i = 1, 2, \ldots, 2^{p-1} - 1 \\
  x - (2i - 1)\lambda & \forall x \in (2(i - 1), 2i] \\
  i = 1, 2, \ldots, 2^{p-1} - 1 \\
  x - (2p + 1)\lambda & \forall x \in [2(2^{p-1} - 1), \infty). 
\end{cases} \tag{6} \]

4. Performance criteria and design guidelines

It is important that the performance for different values of \( p \) be compared on a fair basis. Since the output is cyclo-stationary with period \( p \), the average performance over the cyclo-stationary period used to compare designs via the cost function:

\[ J_\alpha(p) = \frac{1}{p} \sum_{k=1}^{p} E \left\{ \gamma((\ell p + p + d + i)\lambda) \right\} \tag{7} \]

As remarked earlier, for each \( p \), there are four degrees of freedom in the architecture of Fig. 1, namely \( C_p^1 \), \( L_p^2 \), \( H_p^2 \) and the choice of quantization levels in \( Q_p \). The design of each of these elements is discussed below.

- \( C_p^1 \): This controller is designed to minimize \( J_\alpha(p) \) considering \( q_p^d = 0 \).
- \( L_p^2 \): This filter is designed to minimize the variance of \( \bar{\nu}^p \) (the input to the quantizer) considering \( q_p^d = 0 \).
- \( H_p^2 \): This filter is designed to minimize \( J_\alpha(p) \) when \( q_p^d \) is modelled as a white sequence\(^2\) and \( \bar{\nu} \) is considered to be zero.
- \( Q_p \): The levels in the quantizer are chosen to minimize \( J_\alpha(p) \) when both \( \bar{\nu} \) and \( q_p^d \) are present.

Although restrictive, the above framework underlies contemporary work on the signal to noise ratio approach to network control (Braslavsky et al., 2007; Goodwin et al., 2010). Moreover, it is known that this strategy leads to similar insights to those obtained by more general formulations (Goodwin et al., 2010).

Recall that, the control signal is subject to the constraint

\[ \bar{u}_k = \tilde{u}_{\ell k} \quad \text{for } \ell k < p (\ell + 1), \quad \ell \in \mathbb{Z}. \tag{8} \]

This constraint leads to the result that the system, when viewed at period \( \Delta_1 \), is \( p \)-periodic and that the output is cyclo-stationary. A lifted form of the model is used to derive the key results. Hence, for \( k = \ell p \) and subject to the control constraint (8):

\[ x_{\ell p+1} = x_{\ell p+1} = A_p x_{\ell p} + B_p \tilde{u}_{\ell p+1} + K_p \bar{\nu}_{\ell p} \tag{9} \]

\[ y_{\ell p} = C_p x_{\ell p} + D_p u_{\ell p} + D_{p,v} \bar{\nu}_{\ell p} \tag{10} \]

where \( \bar{\nu}_{\ell p} = [\bar{\nu}_{\ell p} \ \bar{\nu}_{\ell p+1} \ \cdots \ \bar{\nu}_{\ell p+(p-1)}]^T \), \( y_{\ell p} = [y_{\ell p} \ y_{\ell p+1} \ \cdots \ y_{\ell p+(p-1)}]^T \) and

\[ A_p = A_p^p; \quad B_p = \sum_{i=1}^{p} A_p^{i-1} B \tag{11} \]

\[ C_p = \begin{bmatrix} (C)^T & (CA)^T & \cdots & (CA^{p-1})^T \end{bmatrix}; \quad K_p = \begin{bmatrix} A_p^{-1} K & A_p^{-2} K & \cdots & K \end{bmatrix} \tag{12} \]

\[ D_p = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ CB & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA_p^{p-2} B & CA_p^{p-3} B & \cdots & 0 \end{bmatrix}; \quad D_{p,v} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ CK & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA_p^{p-2} K & CA_p^{p-3} K & \cdots & 1 \end{bmatrix} \tag{13} \]

where \( 1 \in \mathbb{R}^{p \times 1} \) is a column vector of ones.

Lemma 1 (Design of \( C_p^1 \)). The following controller minimizes (7):

\[ x_{\ell p+1} = A C x_{\ell p} + B C u_{\ell p} + K C y_{\ell p} \tag{14} \]

\[ u_{\ell p} = C x_{\ell p} + D_C y_{\ell p} + u_{\ell p} \tag{15} \]

where

\[ A_C = (A - K C)^{-1}; \quad B_C = \sum_{i=1}^{p} (A - K C)^{-i-1} B \tag{16} \]

\[ K_C = \begin{bmatrix} (A - K C)^{-1} & (A - K C)^{-2} & \cdots & K \end{bmatrix}; \tag{17} \]

\[ C_C = \begin{bmatrix} CA_p^{p-1} + K C \end{bmatrix} \tag{18} \]

\[ D_C = \begin{bmatrix} CA_p^{p-1} & CA_p^{p-2} & \cdots & K \end{bmatrix} \tag{19} \]

\[ a = \frac{C_C^T G_1}{G_1^T G_2} \tag{20} \]

Proof. From (1), (2) and (3) it is seen that the predicted output given data up to time \( k = \ell p \) satisfies

\[ \begin{bmatrix} \hat{x}_{\ell p+1} \\ \hat{y}_{\ell p+1} \\ \hat{y}_{\ell p+2} \\ \vdots \\ \hat{y}_{\ell p+(p-1)+d} \end{bmatrix} = \begin{bmatrix} CA_p^{p-1} & CA_p^{p-2} & \cdots & K \end{bmatrix} (A - K C) x_{\ell p} + \begin{bmatrix} CA_p^{p-1} & CA_p^{p-2} & \cdots & K \end{bmatrix} y_{\ell p} \]
where $\tilde{u}_p = \tilde{u}_p^{\ell}(t-1)$. The optimal control can be derived as

$$u_p^c = C_x \tilde{x}_p^c + D_C \tilde{y}_p + au_p^{\ell}(t-1)$$

where $C_x$ and $D_C$ are as given in (18)–(19). We note however, that the plant state $x_p^C$, used in the above derivation is not available, so an observer is needed.

$$x_{p(t+1)} = A_p x_p + Bu_p^{\ell}(t-1) + K_t (y_p - C_x x_p).$$

Replacing $x_p^C$ by $x_p^C$, (15) is obtained. 

**Lemma 2 (Design of $L^p$):** (i) The optimal filter 1 + $L^p$ is defined by the following equations:

$$x_{p(t+1)} = A x_p + Bu_p^{\ell}(t-1) + K_t (y_p - C x_p)$$

$$u_p^{\ell} = C x_p^{\ell} + D_C y_p + au_p^{\ell}(t-1)$$

$$A_1 = A_p + K_t C$$

$$C_1 = - (C_p + D_C C)$$

where $K_t$ is the Kalman filter gain designed for the plant:

$$\tilde{x}_{k+1} = \hat{\hat{x}}_k + \hat{\hat{\theta}}_k$$

$$\hat{\hat{\theta}}_k = \hat{C} \hat{x}_k + \hat{\theta}_k$$

where $\hat{A} = A_P$, $\hat{C} = C$ and

$$E \left( \begin{bmatrix} \hat{\hat{\theta}}_k \\ \hat{\hat{\theta}}_k^T \end{bmatrix} \right) = \begin{bmatrix} K_p \hat{\hat{\theta}}_k \\ (A_p P^{-1} K + D C) \end{bmatrix} \sigma^2.$$

(ii) The inverse filter, $(1 + L^p)^{-1}$, is given by

$$x_{p(t+1)} = A x_p + Bu_p^{\ell}(t-1) + K_t y_p$$

$$u_p^{\ell} = -C x_p + au_p^{\ell}(t-1) + y_p^c$$

**Proof.** Recall the controller given in (15). For the purpose of the current derivation, note that the controller state is (asymptotically) equal to the plant state. Hence one can equivalently write (15) as:

$$u_p^c = C x_p^{\ell} + D_C y_p + au_p^{\ell}(t-1).$$

Using the plant model (1) and recalling the plant equation in its equivalent lifted form (9)

$$u_p^c = C x_p^{\ell} + D_C (C x_p^{\ell} + \hat{\theta}_p^{\ell}(t-1)) + au_p^{\ell}(t-1)$$

where $A_p$, $B_p$ and $K_p$ are given in (11) and (12). Eqs. (9) and (35) can be seen as a system having process noise $K_p e_p$ and measurement noise $D e_p$. The process and measurement noise have cross-covariance given by $\sigma^2 A P^{-1} K D$. This system can be rewritten in innovations form:

$$x_{p(t+1)} = A x_p + B u_p^{\ell}(t-1) + K_t y_p$$

$$u_p^{\ell} = (C + D_C) x_p^{\ell} + au_p^{\ell}(t-1) + v_p^{\ell}$$

where $K_t$ is the corresponding Kalman gain and $v_p^{\ell}$ is the new innovation sequence. Eqs. (36), (37) are the inverse filter $L^{-1}$ with input $v_p^{\ell}$ and output $u_p^{\ell}$. The corresponding inverse, that is the filter $1 + L^{-1}$, is

$$x_{p(t+1)} = A x_p + B u_p^{\ell}(t-1) + K_t (y_p - (C + D_C) x_p^{\ell} - au_p^{\ell}(t-1))$$

$$v_p^{\ell} = u_p^{\ell} - (C + D_C) x_p^{\ell} - au_p^{\ell}(t-1)$$

This result establishes (25) and (26). Also, since $v_p^{\ell}$ is an innovations sequence, it is i.i.d with minimal variance. This concludes the proof of (i). The inverse filter, as stated in (36), (37) is given by (32), (33).

To design $H^p$, $e_k$ is temporarily set to zero and $d^p$ is modelled as a white noise sequence. Recall that the goal of $H^p$ is to minimize the impact of $d^p$ on the output. From Fig. 1, the input $s_p$ to the filter $1 + L^p$ is

$$s_p = \hat{\hat{\theta}}_p^c + q_p - m_p$$

where $m_p$ is the output of $H^p$. Also, $q_p$ is assumed to be an i.i.d process. The resulting system can be viewed as an LTI system at rate $p$ with input (equal to $m_p$) and output $y_p^c$ can be written as:

$$x_{p(t+1)} = A x_p + B (q_p - m_p)$$

$$y_p^c = C x_p^c$$

where

$$A_5 = \begin{bmatrix} a + D_{e_p} x_p^c + D_{e_p} C_p & 0 & C_p & C_1 & -C_1 \\ B_p & A_p & 0 & 0 & 0 \\ D_C e_p^c & D_C e_p^c & 0 & A_C & 0 \\ 0 & B_C & 0 & 0 & 0 \\ B_0 + K_p D_p + K_p D_p & K_p D_p + K_p D_p & 0 & K_t C_k & K_t C_{k_l} \\ 0 & K_t C_{k_l} & 0 & K_t C_t & A_p \end{bmatrix}$$

$$B_5 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ K_t^2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_5 = [D_p & C_p & 0 & 0 & 0]$$

where $0$ are zero matrices of appropriate dimensions.
Hence, using (59),
\[
\dot{x}_{t+1}^0 = u_t.
\]  

(iii) The controller (with delay system 2p), (input \( y_t \) and output \( u_t \)):
\[
\begin{align*}
\tilde{x}_{t+1}^0 & = \tilde{u}_t, \\
\tilde{x}_{t+1}^0 & = A_C x_{t}^0 + B_C x_t^0 + K_t (\tilde{u}_t + \tilde{a} x_t^0), \\
u_t & = C x_t^0 + D x_t^0 y_t. 
\end{align*}
\]

(v) The controller (with delay system 2p), (input \( y_t \) and output \( u_t \)):
\[
\begin{align*}
\tilde{x}_{t+1}^0 = A_C x_{t}^0 + B_C x_t^0 + K_t (\tilde{u}_t + \tilde{a} x_t^0) \\
v_t &= C x_t^0 + D x_t^0 y_t. 
\end{align*}
\]

\( p \)

5. Example

Many cases have been simulated and, in all cases, \( p = 1 \) turned out to be the best choice. An illustrative case is given below.

The plant (at sample period \( \Delta_t \)) including anti-aliasing filter is modelled \(^3\) by (1).

\[ A = \begin{bmatrix} 0.9 & -0.1 \\ 0.7 & 0.8 \end{bmatrix}, \quad B = \begin{bmatrix} 0.8 \\ 1 \end{bmatrix}, \quad K = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}. \]

Note that this state space system is a stable, minimum phase, LTI system of relative degree 1.

\( C^1, \quad L^p, \quad H^p \) are defined as in Section 4. Then, a full Monte Carlo simulation based on the circuit shown in Fig. 1 is used. (Note that \( q_0^p \) is not modelled as an i.i.d. sequence in the simulations.) \( \lambda^p \) is chosen by a line search to minimize (7) for each \( p \). The results are shown in Table 1. From Table 1 it is clear that \( p = 1 \) is best. In the tested example it gives, approximately, 25% improvement on the output variance over any other \( p \).

6. Conclusions

This paper has studied the control problem that arises when the control signal is implemented over a bit rate constrained communication channel and when the control update rate is, otherwise, unconstrained. Several simplifying assumptions have been made, so as to simplify the analysis tractable. The conclusion, based on the restrictive assumptions made, is that it is best to use 1 bit per sample and hence to choose the control update rate equal to the inverse of the bit rate. More complex scenarios, for example nonminimum phase and or unstable plants are the subject of ongoing research. Note that, in the latter case, one can only expect local stability since the range of a fixed bit quantizer is necessarily finite. Also, more sophisticated designs for the coder/decoder and quantization could be considered. We (boldly) conjecture that \( p = 1 \) is the best choice under very general conditions. In this context, we hope that this paper may inspire other researchers to examine more general scenarios.

\( ^3 \) The innovations variance is taken as 1 without loss of generality since all results are simply scaled by the innovations variance.

### Table 1

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<th>2</th>
<th>3</th>
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<tr>
<td>Best choice for ( \lambda_p )</td>
<td>0.95</td>
<td>0.25</td>
<td>0.14</td>
<td>0.09</td>
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<tr>
<td>Average output variance achieved with ( \lambda^p )</td>
<td>2.3268</td>
<td>2.9363</td>
<td>3.1056</td>
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### References


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3. 3D video and multi-view data.
4. Sampling and combined representations of signals and images.
5. Adaptive systems in signal processing and control.
6. Applications of vector quantization.

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