Event-based sampling for wireless network control systems with QoS

Adrian D. McKernan and George W. Irwin

Abstract—Communications load in a wireless channel can saturate the network when the wireless link between stations is weak. This paper shows that, by using a state-differential event-based sampling scheme with QoS, this load can be reduced such that a control loop closed over that network can remain stable for much worse wireless channel conditions. By varying the event threshold, systems with high state variance will have higher sampling rates than those without, while the overall throughput of the system is reduced to a level which does not saturate the network.

I. INTRODUCTION

Networked Control Systems (NCS) have received much attention in recent years [1]. This paper focuses on the use of wireless channels in feedback control and sampling techniques to improve the stability and performance of such systems. The motivation is that the stability of such closed-loop systems are significantly more likely to deteriorate than with a wired NCS [2].

Many techniques have been tried to improve NCS’s and they can generally be separated into the fields of control design and communications design. With communications design the control system is simply treated as a source of high priority data and a new communications protocol is designed to reduce the sensor-to-controller and controller-to-actuator delays [3].

Rather in control design the network is seen as a source of delay and possible measurement loss. Controllers are therefore designed to be resilient to varying sample rates and delays [4]. However often the assumptions about delays are inaccurate and do not take into the account the dynamics of the network.

More recently a field of research called co-design has emerged which focuses on the interaction of the control system and the network. Sample-rate adaptation changes the sample rate of a controlled plant according to the round-trip delay. This helps extend the range of channel conditions for which a system is stabilisable [5], [6]. However, when there are multiple control loops closed over the same network, it is preferable to also have a control performance metric to adjust the sample rate of the controlled plant. This leads to the idea of event-based control where sampling is dependent on states variations instead of time.

Sample-rate adaptation is one way of reducing the bandwidth utilised by a control system during periods of poor network conditions and event-based control provides another avenue of interest. Event-based control has been used in many applications but is not as widespread as time-driven sampling due to a lack of mature theory.

Event-based sampling and control has obvious applications in networked systems where the transmission of a sample is expensive as it can help to reduce the average sample rate needed [7]. In a wireless network, irrespective of power consumption, communication can be thought of as expensive as the wireless medium is inherently a broadcast medium; sending redundant information simply utilises a scarce time-varying resource to the detriment of other nodes on the network. It stands to reason that only significant information should be sent over the network and that, if the measurements being sampled have not changed sufficiently, then there is no benefit in transmitting them.

This paper presents a new adaptive event-based sampling algorithm. Adapting what constitutes an event according to a QoS metric allows for a fair distribution of available bandwidth. As each node selects when to sample and transmit the extra communication overheads of a centralised coordinator are not introduced.

This paper is organised as follows, in section II The problem is outlined and the sampling algorithm is stated. A example system is given in section III and the efficacy of the sampling algorithm is show through Monte-Carlo simulations in IV. Finally some possible extensions to the work are discussed in section V and conclusions are drawn in section VI.

II. PROBLEM OUTLINE

In this paper we attempt to show the possibility of applying temporal coding to a control system. Simply put temporal coding is limiting the amount of data transmitted to only that which is of use. In information theory data is only information if it has a high entropy, that is to say if there is a low probability that the data can be estimated. In a Wireless network Control System (WNCS) context this means limiting transmission of sampled states when there is little difference in successive samples.

Event-based systems sample once a threshold is reached. In [7] periodic and event-based sampling, where the system is sampled continuously after the threshold is reached, were studied and event-based control was shown to give a three-fold reduction in error variance over periodic control. The discrete case (sporadic control) is dealt with in [8], the system states are observed at regular intervals and once they are larger than a set threshold a sample is taken and then the sampler enters an inactive period.

This paper presents state-differential sampling with Quality of Service (QoS). Similar to sporadic control, the states
are observed locally (Figure 1) at a constant rate until an event is detected, when a sample is taken and transmitted to the controller. The observations then enter an inactive period. Events are defined here as the observed state differing by more than a certain value from the previous sample. This value will vary depending on a QoS metric.

Firstly, states are observed at a regular interval $T_{local}$. If there has been a change in the states greater than a threshold $\delta$ (Figure 2) since the last time the sampled states were transmitted then a sample is taken and transmitted, to the controller. The observations enter an inactive period $T_{wait}$ (Figure 2b) where samples can not be taken. This means that while locally the states are observed at a constant rate of $T_{local}$, they are only sampled and transmitted to the controller at varying multiples of $T_{local}$ and hence the input is only updated at multiple of $T_{local}$.

As the network can only maintain a maximum throughout, under even ideal wireless conditions, equivalent to a single system being sampled at $T$, then the maximum sampling rate will be limited by the sampling period $T$. However, as increasing the local sample rate to $T$ increases the lag time between the states varying by $\delta$ and an event being detected. Therefore $T_{wait}$ (1) is selected to give the maximum sample rate $T$ which will not saturate the network.

$$T_{wait} = T - T_{local}$$  \hspace{1cm} (1)

In an IEEE 802.11 wireless network packets are positively acknowledged. If the wireless channel conditions are non-ideal then some packets may arrive in error and not be acknowledged and also any acknowledgement received may also be corrupted. When a packet is not successfully acknowledged it is retransmitted until a certain limit (nominally 6 times for IEEE 802.11b). The contention window is also doubled, up to a maximum of 6 times, for each non-positively acknowledged transmission before being reset by a successful transmission. This increases the delays as stations spend longer contending for transmission and if the inter-arrival time of new packets (i.e. samples) remains the same this will lead to queue build up. Queue build up in simple FIFO queues causes newer packets to wait for older ones to complete transmission.

The effect of retransmission and extended contention periods is that during periods of harsh wireless channel conditions the available bandwidth of the system is reduced. Therefore it is necessary to reduce the bandwidth used by the control system during these periods.

In [5] the sampling period for a WNCs is varied depending on the last recorded round-trip delay and in [9] the sample rate is varied to maintain a 5% packet loss. The limitation to this is that, in the case were multiple control loops are closed over the same network the bandwidth of each control loop is only dependent on the QoS metric used. By having an event-based control system using state-differential sampling the sampling threshold can be varied depending upon a QoS metric. The increasing threshold means that the average sample rate will be reduced. This leads to the sample rate being chosen by both a QoS metric and a Quality of Performance (QoP) metric. Resulting in plants with high state variance having a higher bandwidth than those with a lower variance and an overall drop in network load.

Within a packet based network the overhead of packetisation and contention is high compared to the time taken to send the contents of the packet. Therefore it is reasonable to prefer to send fewer packets with a larger payload. The idea of event-based sampling can be extended to model based control techniques, were equi-sampled observations are needed to update models, by sending the last several observations each time an event occurs. These equi-sampled observations could be used to converge observers or predictive control models.

An important factor in state-differential sampling is that each node independently decides when to transmit a sample. This eliminates communications overheads from a central
coordinator delegating sampling rates or slot times. This distribution of bandwidth control is in keeping with the philosophy of IEEE 802.11 networks. Here each station will increase its contention window if a positive acknowledgement is not received and also it may reduce its transmission rate through Automatic Rate Fallback [10].

III. NUMERICAL EXAMPLE

A cart-mounted inverted pendulum was selected as an application study and being open-loop unstable constitutes a hard-real-time application.

![Cart-mounted inverted pendulum](image)

Fig. 3: Cart-mounted inverted pendulum

The target application is shown in Figure 3. Here \( \theta \) is the angle of deviation of the pendulum from the vertical, which should always be zero, and \( d \) is the lateral position of the cart. The input to the system \( u \) is the force acting on the cart. The problem is to regulate the position of the cart through choice of Force \( F \) while maintain a stabilising the inverted pendulum.

The general continuous state model is given in (2) with state matrices [11] (3).

\[
\begin{align*}
\dot{x} &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) + w(t)
\end{align*}
\]

(2)

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & -b & 2.673 & 0 \\
0 & 0 & 0 & 1 \\
0 & -0.455 & 31.182 & 0
\end{bmatrix},
B = \begin{bmatrix}
1.818 \\
0 \\
0 \\
4.545
\end{bmatrix}
\]

(3)

The state vector \( x(t) \) is \( [\theta \ \dot{\theta} \ \dot{d} \ \ddot{d}]^T \). the parameter \( p \) is,

\[
p = I(M + m) + Mml^2
\]

(4)

The definitions and values of the physical parameters used are given in Table I. Substitution of (3) into (2) produces the continuous state representation

\[
\begin{align*}
\dot{x} &= \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & -0.182 & 2.673 & 0 \\
0 & 0 & 0 & 1 \\
0 & -0.455 & 31.182 & 0
\end{bmatrix} x + \begin{bmatrix}
1.818 \\
0 \\
0 \\
4.545
\end{bmatrix} u \ 
(5)
\]

A continuous-time Linear Quadratic Regulator (LQR) was designed with \( Q = \text{diag}(1000 \ 0 \ 100 \ 0) \) and \( R = 1 \), and this gave the constant feedback gain matrix \( F \).

\[
F = \begin{bmatrix} -31.6 & -21.8 & 77.1 & 20.4 \end{bmatrix}
\]

(6)

The observations were subjected to a Gaussian measurement noise \( w(t) \), with a mean of zero and variance equal to 0.0001.

IV. RESULTS

Before the complexities of a network were added the equi-sampled and state-differentially sampled systems were both implemented locally, with actuation being provided by a zero-order hold. In Figure 4 the locally controlled equi- and state-differentially sampled, with a constant \( \delta \) of 0.001 and 0.01, plants are shown and there is no difference in performance.

![Angular response for locally controlled plant with constant sampling rate and state-differential sampling](image)

Fig. 4: Angular response for locally controlled plant with constant sampling rate and state-differential sampling.

A. Wireless control

The maximum sampling rate \( T \) can be derived from the maximum bandwidth of channel available for data after all overheads. For a IEEE802.11 network the maximum sampling [5] rate is \( T = 2ms \). If \( T_{\text{local}} = 1ms \) then

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Mass of cart</td>
<td>0.3kg</td>
</tr>
<tr>
<td>m</td>
<td>Mass of pendulum</td>
<td>0.1kg</td>
</tr>
<tr>
<td>b</td>
<td>Friction of cart</td>
<td>0.1N/m/s²</td>
</tr>
<tr>
<td>l</td>
<td>Length of pendulum</td>
<td>0.7m</td>
</tr>
<tr>
<td>I</td>
<td>Inertia of pendulum</td>
<td>0.001kg/m²</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to Gravity</td>
<td>9.8m/s²</td>
</tr>
</tbody>
</table>

TABLE I: Physical properties of the cart-mounted inverted pendulum.
Sampling Frame Average Average Average
policy error ratio ITAE sample rate delay
State
differential
0% 0.0868 0.0021 1.9236
6% 0.0868 0.0021 3.1523
14% 0.0919 0.0025 6.1592
18% 0.0941 0.0028 9.2317
20% 0.0975 0.0030 11.0615
Constant
sampled
0% 0.0874 0.0020 1.8550
6% 0.0877 0.0020 5.5606
14% 24.6309 0.0020 46.2370
18% 6.4412 \times 10^{-9} 0.0020 188.9921
20% 6.4412 \times 10^{-9} 0.0020 360.1172

TABLE II: Performance of varying state-differential sampling under different channel conditions (average of 5 Monte-Carlo step responses) for a single control loop

\( T_{wait} = 1ms \). As with the locally controlled example, the actuator has a zero order hold and holds the current control action until a new packet arrives.

The QoS metric used to vary the event threshold was round-trip delay and the state used for event detection was \( \delta \) with \( \delta_{min} = 0.001 \text{ rad s}^{-1} \). The update policy for \( \delta \) was

\[
\delta = \begin{cases} 
0.001: \tau_{rtd}(t_{k+1}) < 10ms \\
0.005: \tau_{rtd}(t_{k+1}) < (u + 1) \times 10ms \\
0.05: \tau_{rtd}(t_{k+1}) \geq 90ms 
\end{cases}
\]

(7)

In order to simulate the behaviour of the state-differential sampling with QoS and that of the equi-sampled WNCS, Simulnet ([2]) a set of Matlab S-functions which simulate an IEEE 802.11b wireless network was used. Firstly a single control loop for each sample scheme was simulated over networks of varying wireless channels. Each case was simulated 5 times with progressively worsening wireless channel conditions for each case. To illustrate the wireless conditions a nominal Frame Error Rate (FER) is stated. This is the FER that would be experienced by a constant packet source sending one packet every 1ms.

Table II lists the results for both equi-sampled and state-differential sampling with increasing FER. The Integral of Time multiplied By Absolute Error (ITAE) in (8) is used to compare performance over the multiple runs as it highlights slow transients [12].

\[
ITAE = \int_{0}^{\infty} t|\epsilon| dt 
\]

(8)

The average delay for the state-differential sampled case is only 11ms with a FER of 20%. However with an FER of only 14% it already reaches 46ms for the equi-sampled case. From Figure 5a, it is obvious that the equi-sample system becomes unstable between 3 and 4s and this is reflected in the increased ITAE of 24.6 (Table II).

B. Peer contention

As mentioned earlier the maximum bandwidth available in an IEEE 802.11b network is equivalent to a single plant sampled at 2ms. Therefore, as the number of stations increases the sample period of each constantly sampled station must increase from 2ms to 4ms. For the event triggered system the inactive period \( (T_{wait}) \) will be increased to 3ms.

Table III shows the performance metrics for both equi-sampled and state-differentially sampled plants when two control loops are closed over the same network. As before the state-differentially sampled plants remain stable and maintain a good performance; with an ITAE of less than 0.1 except for an FER of 18% when the ITAE is 0.1086. This is due to the one step response which can be seen in Figure 6b, which had a maximum pendulum angle of 0.3216 and a minimum of -0.2922 radians form the vertical. Although this is a minor degradation in performance compared to the other state-differentially sampled step responses it still remained stable. However it can clearly be seen from Figure 6a that all the equi-sampled plants become unstable between 4 and 5 seconds.

The delay for both the equi-sampled and state-differentially sampled plants for the runs with a FER of 18% are shown in Figure 7a. At 4s the equi-sampled delays increase to over 100ms. However the state-differentially sampled plants do not experience this delay as the threshold is increased (Figure 7b) and thus the intersample period is
increased (Figure 7c) thereby decreasing the sample rate and preventing the network from being saturated.

V. Future work

While state-differential sampling with QoS presents an interesting idea on how to improve the stability of WNCS it does present some design considerations. The selection of the event threshold update policy (7) was taken form empirical data of sampling rates and performance index for a locally controlled plant at different fixed event thresholds. This leaves room for optimising this policy. Also currently only static controller gains which have not been expressly designed for transport delays, event-based or variable sampling are used to illustrate the concept. If a gain scheduled controller designed for variable delay such as [13] were to be included then an improvement in performance or the range of network conditions for which the system is stabilisable might occur.

VI. Conclusions

In this paper a new form of event-based sampling is presented. In the form of one which samples depending on both QoS and QoP metrics. This allows for the requested bandwidth of multiple control loops to be reduced when the network condition deteriorate while prioritising those loops which are experiencing greater state variance. The veracity of this approach has been shown with Monte-Carlo simulation results. Specifically the new state-differential sampling with QoS has increased stability with respect to worsening wireless channel conditions than that of a traditional time based sampling.

VII. Acknowledgments

The authors gratefully acknowledge the contribution of Department for Education and Learning and reviewers’ comments.

REFERENCES

Fig. 7: Plots of round-trip delay, threshold levels and intersample periods for the case of two control loops closed over a wireless channel with a nominal FER of 18%