Co-design in Heterogeneous Wireless Networked Control Systems

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Abstract: This paper presents a co-design approach for heterogeneous wireless networked control systems (HWCS). An isolated design of controller and network architecture for the networked control system does not guarantee good performance if network dynamics are not included in the loop. Estimation of the delay, packet loss and errors is important especially when the control information passes through a heterogeneous wireless network. Co-design approach for the HWCS suggests that the control system must accommodate the variations in network quality of service or vice versa, so that it will not affect the stability and performance of the system over network.

Keywords: Networked Control System, Co-design approach, Heterogeneous networks, Quality of service, Quality of Control.

1. INTRODUCTION

Wireless networked Control Systems are getting popular with the recent advancements in high data rate, secure and low cost wireless network protocols. Wireless networks are easy to install and suitable for places far from infrastructure. However, wireless networks put some challenges too. There are more packet losses as compared to wired networks, the bandwidth is limited, interference may strongly effect signal quality and there are more delays on average, depending upon the environment of operation. The networked control system (NCS) requirements are different from data networks in that they communicate small data packets as compared to voice or video applications, with emphasis on guaranteed quality of service (QoS) and bounded delays.

In the literature, the terminology of heterogeneous and hybrid network is interchangeably used. For example, (Liu et al., 2003) describes a hybrid network by placing a sparse network of base stations in an ad-hoc network. The base stations are connected with a high-bandwidth wired network and act as relays for wireless nodes. (Dai et al., 2008) presents a handover algorithm to connect between WLAN and WiMAX and here it uses handover between hybrid networks. However, based on some of the recent publications, we differentiate between these two type of networks. Heterogeneous networks are defined as the one which uses the same medium of communication with at least 2 different protocols, e.g. a network composed of WLAN 802.11 and WiMAX 802.16 as discussed in (Javaher et al., 2006) and (Vidal et al., 2004). On the other hand, a hybrid network utilizes at least two different medium of communication for each tier, thus forming a heterogeneous network. A lot of research work has already been done on the control and diagnosis over networks for distributed applications like (Vatanski et al., 2009) and (Zhang et al., 2004). As a common practice, control over network resources is not considered by control engineers. Instead, controller is modified to accommodate delay and missed data due to communication network imperfections. In (Sename and Fattouch, 2005), robust control of bilateral teleoperation
systems subject to communication time delays is considered. An upper bound of network delay is estimated in case of delay independent stability is not possible over the communication network. In (Feng and Qingguan, 2008), a heterogeneous wireless networked control system with a PID controller combined with a modified Smith predictor (MSP) is discussed. Thus no network delay model and online estimation is needed by this implementation. There is a recent development in co-design approach for Networked control systems, which takes into account the constraints posed by both of the control and network domains as studied in (Mechraoui et al., 2009), (Boughannet et al., 2009) and (X. Nguyen et al., 2009). Our work is oriented towards co-design of networked control systems communicating over heterogeneous wireless networks.

Fig. 1 shows a general structure of the traditional one-tier wireless networked control system where sensor data and controller command are sent through a wireless network. The delays introduced in the loop are from the sensor to controller $\tau_{sc}$ and controller to actuator $\tau_{ca}$. The computational delay $\tau_{c}$ is assumed to be very small as compared to $\tau_{sc}+\tau_{ca}$. The delay characteristics and packet losses of the network are need to be evaluated in order to verify its effect on the control system.

This paper is organized as follows. Section II provides an introduction and basics of the heterogeneous wireless networked control systems. Section III addresses the key components of co-design problem in HWNCS. Section IV presents the simulation results of a scenario with the co-design approach. This paper concludes with Section V. References are added at the end.

2. HETEROGENEOUS WIRELESS NETWORKED CONTROL SYSTEMS (HWNCS)

A heterogeneous wireless network is defined above as a combination of at least 2 wireless network protocols. An example of HWNCS is shown in Fig. 2 to illustrate the concept. For long range communication, a heterogeneous wireless network utilizing 2 tier network architecture is quite effective keeping in view the bandwidth and bit error rates in the overall end to end performance (Zenash et al., 2009). In our approach a medium range WLAN network is used to communicate between sensor-controller and controller-actuator path. These gateways are connected to broadband network with traffic prioritization for the control information (tracking, formation control, remote teleoperation etc). It should be kept in mind that the network speed variations and error rates are more serious problems in control systems than in general purpose computing networks where some data loss is permitted for a graceful degradation in service quality or by resending the same information. QoS provisions in broadband networks e.g. in WiMAX, can be utilized in our case to allow guaranteed realtime flows for control data. An optional local loop is also shown in the HWNCS shown in Fig. 2, which ensures stability (shown as a dotted block in the feedback path) in case the plant is unstable. In distributed systems, autonomy is the main concern, so a local control is necessary. This is important because reliability and determinism in wireless networks is still a research area. An interfering source with a noise power greater than the useful signals can effect the performance. Frequency hopping is one of the method for channel blacklisting while combating with interference. In addition, if network load is increased up to the point where network is unable to hold more data, the plant cannot be left un-supervised waiting for a command from a distant controller. In Fig 3, a search and rescue scenario is shown, which utilises HWNCS. The mission controller operating from distance sends the urgent messages from search team to call rescue operation through mobile robots.

3. CO-DESIGN APPROACH

Control and communication co-design is an important consideration when control related information (sensor data or actuator command) is needed to be sent over a network. However, for distributed control applications, usually, controllers communicate with each other for cooperative task management like global consensus, formation control and distributed computing (Fox and Murray, 2004).

3.1 Network Quality of Service (QoS)

QoS is a broad term that is defined in different perspective. Researchers in Networks and communication domain define it from the Network QoS perspective and consider QoS as the promising performance that an underlying communication network can deliver while efficiently utilizing network resources. Thus ensuring QoS in a network...
means to find optimal paths for real-time data (with certain end-to-end delay requirements) and minimize delay as much as possible to keep it within bounds. Delays, packet losses, errors (incorrect values) are some of the important parameters related to network QoS. In (Angermann and Kamann, 2002), the author evaluates different structures for QoS cost functions and presents a simulation to demonstrate the influence of various parameters. An approach to quantify network QoS is discussed in (Mecracou et al., 2009) by introducing a network rating function (NRF). This function given in Eq. (1) and calculates the ability of network to deliver sufficient QoS for our data.

\[ N.R.F = W_{RSSI}.N_{RSSI},i + W_{NL}.N_{NL},i + W_{D}.N_{D},i \tag{1} \]

where,

\[ W_{RSSI} + W_{NL} + W_{D} = 1 \tag{2} \]

where \( W_{RSSI} \), \( W_{NL} \) and \( W_{D} \) are weighting functions of received signal strength indicator (RSSI), network load (NL) and delay (D) respectively. \( N_{RSSI},i \), \( N_{NL},i \) and \( N_{D},i \) indicate the scores of wireless network interface and are defined below in Eqs. (3), (4) and (5). \( N_{RF},i \) is between 0 and 1. \( Wi \) is the weight of the factor i, which emphasizes the importance of each contributing factor and \( N_{i,j} \) represents the normalized score of the interface j for factor i.

\[ N_{RSSI},i = \frac{\exp^{P_{r}}}{\exp^{P_{s}}} \tag{3} \]

\[ N_{NL},i = \frac{1}{\exp^{P_{l}}} \quad 0 \leq NL \leq 1 \tag{4} \]

\[ N_{D},i = 1 \tag{5} \]

if RSSI > threshold and 0, if not

Where \( P_{r} \) and \( P_{s} \) are received and sent signal powers respectively.

QoS adaptivity is defined in (Michaux and Lepage, 2002) as the ability of the network to respond to the varying QoS requirements of applications needs, e.g. voice, data, video etc. However, here we refer to our control system application which means how QoS in a heterogeneous network can guarantee a promising flow of control related information despite other flows and queuing delays over the network.

### 3.2 Quality of Control (QoC)

The quality of control in a feedback control system refers to the quality of performance that is achieved as per control objectives. A measure of control quality can be the regulation or tracking error. Usually, integral of the absolute error (IAE) and integral time absolute error (ITAE), are used to evaluate the control system design and performance. IAE is the integral of the absolute value of the error and ITAE is the integral of the time multiplied by the absolute value of the error. Their mathematical formulation described in (Franklin et al., 1994) is as under:

\[ I.A.E = \sum_{k=0}^{k_{f}} | e_{k} | \tag{6} \]

\[ I.T.A.E = \sum_{k=0}^{k_{f}} k \cdot | e_{k} | \tag{7} \]

Where \( e_{k} \) is the error between the actual and reference trajectories between the initial and final times of the evaluation period in discrete time. ITAE weights the steady state errors heavier and relaxes the transient response, whereas IAE weights all errors equally.

### 3.3 Co-design approach

The general purpose Co-design framework for heterogeneous wireless networked control systems is presented in Fig. 4. First of all, global objectives and specifications are generated according to the mission requirements. Then controller is designed in Matlab/Simulink environment for the dynamic system which gives suitable control quality. At parallel, wireless network architecture is designed by utilizing heterogeneous communication protocols, keeping in view the cost, range and energy requirements. The two layer architecture is connected through a gateway, which further adds dynamics in the loop in terms of packet losses, queuing and processing delay.

End-to-End quality of service in the wireless network architecture is evaluated in a network simulator under worst conditions. The resulting delay, jitter and packet loss profile is added in the control loop for the network performance achieved. If it is found satisfactory, the design is successful, otherwise, control and network design has to be tuned for improved performance. In the literature, a co-simulation approach is also used for evaluation of the co-design performance. This includes OPNET-Matlab, NS2-Matlab, NS2-Modelica as described in (Hasan et al., 2007) and (Al-Hammouri et al., 2007). However, co-simulation of NCS is limited due to the problems regarding synchronization of two softwares and scalability of network architecture which affects directly, the speed of the simulation.

### 4. SIMULATION

A scenario is simulated to explain the co-design problem in heterogeneous networked control systems. It was noted that the delays experienced in a HWCN are dependent on many factors e.g. protocol of underlying networks,
competing nodes for medium access control, multi path effects, environment and interfering sources etc. The transmission rate is assumed the same for each node on the channel and remains unchanged with time. However, for simplification, only delays and packet losses introduced by the wireless protocols are considered. All computational delays, queuing delays and errors in communication are neglected. Control signaling in each protocol actually adds up in round trip time (RTT) which includes all the delays from sensor transmission to the command reception at the actuator end.

4.1 Controller design for a D.C Motor.

The plant under consideration is a D.C motor with a 2nd order transfer function as shown in Eq. 2 below with \( A = 107 \, \text{rad/s} \cdot \text{volt} \) and two poles corresponding to time constants \( \tau_1 = 502 \, \text{ms} \) and \( \tau_2 = 1.4 \, \text{ms} \) respectively (Bebra et al., 2007). The continuous time transfer function is given as:

\[
H(s) = \frac{A}{(1 + \tau_1 s)(1 + \tau_2 s)} \quad (8)
\]

A discrete PI controller \((\text{with } K_p = 46.1x10^{-3}, K_i = 93.1x10^{-3})\) is used to obtain satisfactory control performance (response time \( \text{br} = 300 \, \text{ms} \), steady state error = 0) of the closed loop system. Using the criteria of at least 10 samples in the rise time will result in a sampling period (Ts) of 30 ms. The closed loop bandwidth is 11.5 rad/sec. Using another sampling rate criteria:

\[
0.2 < \omega T s < 0.6 \quad (9)
\]

For us, the sampling period can vary b/w 17.4 ms and 52.2 ms. Jitterbug is used for the delay effect analysis (Lincoln and Cervin, 2002). The quadratic cost function below in Eq.9 as follows:

\[
J = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} (y^2(t) + u^2(t))dt. \quad (10)
\]

This function has been evaluated for different sampling periods in the interval 5 to 120 ms (4 times the sampling period), and for variable delay ranging from 0 to 100 percent of the sampling interval. As can be observed from Fig.6, delay equal to 2 times the sampling period can tolerate sufficient packet losses with a greater cost. However at 120 ms, packet loss greater than 10 percent can even destabilize the system as the cost \( J \) goes to infinity.

Delay, especially jitter that is caused by the network in a control loop can induce instability. The stability of the control system with varying time-delay can be proved by evaluating the jitter margin which defines the amount of additional delay that a closed loop system can tolerate without going unstable. This delay can vary with in the bounds given by the jitter margin \( J_{\text{max}} \) as worked out in (Cervin et al., 2003).

4.2 Control over Heterogeneous wireless network.

In the second scenario, a heterogeneous wireless network is simulated in OPNET Modeler to simulate the mobile robot clusters for search and rescue purposes as shown in

Fig. 3. In case of an emergency, a sensor team member sends instant message to a rescue group node to do some action. Three WLAN subnets are considered which are connected via WiMAX broadband network. Each WiMAX subscriber station in the three subnets acts as a gateway to send data to the WiMAX base station. The WiMAX base station is further connected to the controller station via Ethernet. Node mobility is not considered here for simplicity. Node 4 in subnet 1 is configured with a priority flow over WiMAX using real time polling service (rtPS) of 1000 bytes simulating control information as compared to heavy flows on other nodes.

OPNET provides only 2 modes (DCF and PCF) in WLAN model. It is important to note that within each of the subnet, WLAN DCF mode is used as PCF is not optimized and can increase delays as mentioned. This can be observed in Fig. 7 where PCF flows are configured at each node. The WLAN access point wastes a lot of time asking every node if it has some data to send over PCF slots. This increases average delay at each node, thus resulting in poor performance as compared to DCF as shown in Fig. 8.
The maximum average end to end delay obtained with a prioritized reserved flow at node 4 is around 5 ms (10ms for $T_{ac} + T_{co}$) which is less than the sampling time of 30 ms. This is shown in Fig. 9 where delay and its variation (jitter) are plotted for each node in WLAN subnet 1. Any sample exceeding the sampling time will be discarded or considered as lost packet. This delay is injected in the control loop where continuous time plant is considered with a discrete time controller and transport delay which is added between sensor and controller as well as between controller and actuator nodes.

As shown in Fig. 10, the plot shows degradation in performance due to increased overshoot. This is obviously due to added delays in the control loop. Methods for delay estimation and control of time delay systems used by the control engineers can be augmented to maximize performance by gain adaptation or robust control.

As presented in our scheme, the control and network parameters are tuned in the co-design approach to get a better response. The network tuning is a challenging task specially with a connection less protocol (e.g., WLAN). Here, we have introduced 'Smith predictor' in the control loop for the stable plant which cancels out the effect of delays due to the network. Fig. 11 shows the response of the motor with a variable delay that has a constant value of 30 ms loop delay and 50 ms max variable loop delay. The motor is not only stable but also showing better response. Here network tuning is not used that requires a control of the wireless networks in the two tiers. However, in our future work, we will formulate an end-to-end QoS for wireless network which will be controlled with respect to control performance.

5. CONCLUSIONS

A Co-design approach for a heterogeneous wireless networked control system is proposed by using a parallel
Fig 11. Motor performance with Smith predictor.

design for control and network architecture and then combined interdependent tuning for best control response
despite changes in network conditions. A detailed investigation is however, needed to define a relationship between
QoS and QoC by combining NRF with IAE or ITAE.

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