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Model Prediction Algorithm and Co-Design of Time Delayed Networked Control Systems

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Abstract**—**The Unmanned Aerial System (UAS) uses moderately complex, embedded hardware and software for realization of the control objectives. In such systems, there is a necessity for networking various sensors, actuators and the controllers through a wireless medium. This leads to the need for careful examination of the quality of both the network and the control in a holistic sense, since the feedback loop is closed over the wireless network. We propose a co-design of control and communication algorithms to mitigate the time delay effects and to ensure certain degree of resilience. Modified Smith predictor and the Dynamic Matrix Control are the control strategies considered. Performance error of control loop becomes larger with the increase in network time delay, which would affect system stability. IEEE 802.15.4 wireless network standard is adopted in the present work for network environment. Higher priority is assigned to time-critical task in the mission mode of aerial vehicles through the optimized tuning of wireless network protocol parameters, in proportion to the associated control loop error values. The simulation results show the effectiveness of the controller designs, and verify the co-design algorithms as well. Co-design helps to alleviate the negative effects of time delay arising in the signal communicated through the wireless network.

Keywords**—**Networked control systems, unmanned aerial systems, modified Smith predictor, dynamic matrix control, IEEE 802.15.4 wireless network standard, co-design.

I. INTRODUCTION

UNMANNED Aerial Systems (UASs) represent systems that comprise air borne Unmanned Aerial Vehicle (UAV), the ground station and other elements such the associated sensors, actuators and controllers. The UAVs are designed with embedded autopilot systems, with an underlying data communication network leading to Networked Control Systems (NCSs) [1]. UAVs are reusable systems with light weight, low cost and low power. They are supposed to do the task assigned and come back without human assistance/control in autopilot mode, while it is remotely operated during the radio control mode. There are many advantages for using UAVs that include: operation in areas that are not reachable and dangerous for humans; no need for qualified pilots; and accomplishment of tedious and dull tasks with precision. The greatest uses of UAS are in military applications. They are also used in a small but growing number of civil applications. A powerful autopilot system can guide all the activities of unmanned vehicle such as take-off, ascend, descend, trajectory following and landing. However, autopilot needs to communicate with ground station for position updates, generate control inputs for control mode selection, and receive broadcast from GPS to servo motors on UAVs [2].

In UASs, the various sensors, actuators, and controllers are invariably networked and the feedback loop is closed through a wireless medium. This leads to the necessity for careful examination on the quality of the service of networks in the control and instrumentation arena in a holistic sense; because, unlike communication linkage, the control networks need to work in a mission mode. They have to accomplish the tasks as prescribed, within a time frame and with a greater degree of certainty. These real time requirements are usually decided by the criticality of the processes being controlled in the mission operation. We can use the Quality of Control (QoC) and the Quality of Service (QoS) for dealing with the performance requirements of controller part and the network part respectively.

This paper focuses on the exploration of feasibility of some methods and algorithms, to improve the QoC performance by the control system as well as QoS provided by the network, through a joint design of control and communication network. Control performance is linked with the wireless network parameters, and co-design method ensures the total system performance and stability that are otherwise degraded by the usage of wireless networks [3].

In UAS, measurements are regularly transmitted from various sensors to the embedded controllers through the network. The control algorithm waits for all measurements before computing the control signals as per the control laws. Command signal is computed and transmitted as soon as possible, through the network, to the system actuators. Introduction of wireless networks in to UAS control loops poses new challenges such as variable time delay, packet disorder and packet dropouts, along with numerous advantages. Packet dropouts arise as a consequence of congestion in network or contention for channel and thus it may be treated as time out packets or lost packets [4]. Wireless protocol standard IEEE 802.15.4 Medium Access Control (MAC) [5] is used for simulating the network environment in this work.

The main contributions of the present work are following: The network time delay effects on the system performance and

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stability have been investigated. Two control design methods using Modified Smith predictor and Dynamic Matrix Control (DMC) algorithm are considered in order to overcome the time delays' adversarial effects, and the effectiveness of designs are verified. These methods are well known for control designs involving delays and model uncertainties. Co-design algorithms are proposed for the achievement of desired performance of critical tasks with real time constraints. While considering the real time constraints, the tasks of multiple UAVs fall into the classes of different priorities. QoC is monitored in terms of quadratic error costs, and depending on the priority status, various protocol parameter values have been tuned to reduce the average time delay for medium access for a particular task of UAVs. When the network traffic load increases (resulting in poor QoS), the prioritized MAC parameters cause a delay enhancement in channel access. So as to keep the good performance of high priority task, the sampling of soft real time processes are delayed, within the tolerance limits of the system performance. Simulation results confirm the performance enhancement with the proposed algorithms for co-design. IEEE 802.15.4 MAC parameters like *macCSMABackoff*, *macMaxFrameRetries* etc. have been tuned optimally to minimize the network delay for time-critical applications. All simulations were done on MATLAB® platform.

Remaining part of the paper is organized as follows: Section II provides the basics of NCSs, QoS & QoC requirements, and joint design concept of control and communication in wireless networked control systems. Section III explains Modified Smith Predictor used. Section IV describes the algorithm for Dynamic Matrix Control. The adaptive tuning of IEEE 802.15.4 MAC parameters is given in Section V. Simulation results and discussion are presented in Section VI. Paper is concluded in Section VII.

II. NETWORKED CONTROL SYSTEM MODEL

As mentioned in the Section I, there are situations where the networking in control systems becomes inevitable. Such NCSs are spatially distributed systems, in which, the communication between plants, sensors, actuators and controllers, is facilitated through a shared band-limited digital communication network due to physical limitations. Figure 1 shows the diagram of NCS connected over wireless network (WNCS). Plant is physically connected with sensors and actuators. The controller and the plant are physically located at different locations and are directly linked by a wireless network and forming the closed-loop for control. The controller receives packets from sensors and generates the control signals. These signals are transmitted to the actuators over the network.

However, the use of a shared network, instead of several dedicated independent connections, introduces new challenges, essentially the definiteness in establishing the connectivity and the resilience of control. Challenges include random time delays, delay jitter, packet dropouts and disorder in packet arrival [6],[7].

For the satisfactory performance of any control system, one has to ensure greater degree of robustness to tackle all kinds of uncertainties and facilitate control with certainty. Best outcome will only be possible through a joint design or co-design approach incorporating both the control and communication aspects.

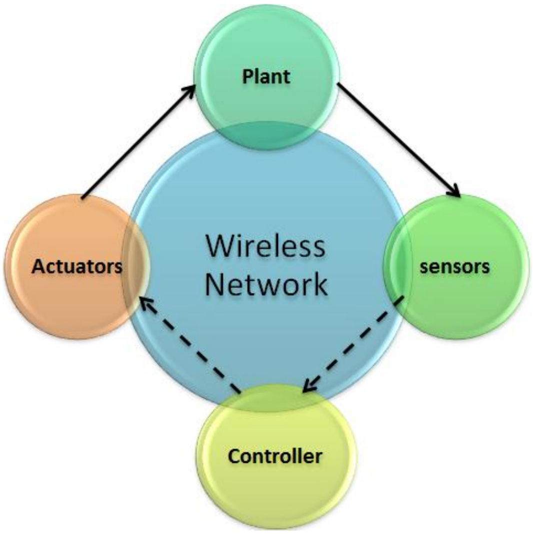

Figure 1 Wireless Networked Control Systems (WNCS)

A. Modeling of NCS

In order to obtain the desired performance or improved performance, we need to select the control design strategy. Here we develop the design specifications as follows:

A linear time invariant single-input single-output NCS is considered where the input is delayed by τ which is assumed to be constant.

$$\begin{gathered} x_{(t)} = Ax_{(t)} + B_{(u-\tau)} \\ y_{(t)} = Cx_{(t)} \end{gathered} \tag{1}$$

with $x \in \Re^n$, $y \in \Re^l$, $u \in \Re^m$. Here x represents the state variables, y stands for output variable, and u represents the control input variable.

The discrete time representation of above equation is

$$x_{(kh+h)} = \Phi x_{(kh)} + \Gamma_{0(\tau)} u_{(kh)} + \Gamma_{1(\tau)} u_{(kh-h)} \tag{2}$$

where

$$\Phi = e^{Ah}$$

$$\Gamma_{0(\tau)} = \int_0^{h-\tau} e^{A\lambda} B d\lambda$$

$$\Gamma_{1(\tau)} = \int_{h-\tau}^{h} e^{A\lambda} B d\lambda$$

Equation (2) is an exact discretization of Equation (1) expressed in terms of periodic signals $x_{(kh)}$, $u_{(kh)}$, $u_{(kh-h)}$.

Suppose NCS is with time-varying and uncertain delay τ^k, then

$$x_{(kh+h)} = \Phi x_{(kh)} + \Gamma_{0(\tau^k)} u_{(kh)} + \Gamma_{1(\tau^k)} u_{(kh-h)} \qquad (3)$$

where

$$\Phi = e^{Ah}$$

$$\Gamma_{0(\tau^k)} = \int_{0}^{h-\tau^k} e^{A\lambda} B d\lambda$$

$$\Gamma_{1(\tau^k)} = \int_{h-\tau^k}^{h} e^{A\lambda} B d\lambda$$

Detailed description on this NCS modeling can be found in [8].

B. *Co-Design of Control and Communication in WNCS*

In order to predict and optimize the control performance of WNCS, a co-design of both the control system with appropriate control structures and algorithms and the communication system with suitable protocols is proposed. Different and often competing trade-offs have to be taken into consideration for designing both the control system and the communication system. For example control performance may be improved by sampling more frequently, requiring more communication bandwidth. Therefore, WNCS design should involve both control system and communication system design together. There are three general approaches to the joint design of control and communication in the literature [9]. In one of those approaches, communication protocols and control algorithms are jointly designed for a given control application, which is adopted in this paper. The WNCS designer can use degrees of freedom of both the control system and the communication system to improve control performance adaptability.

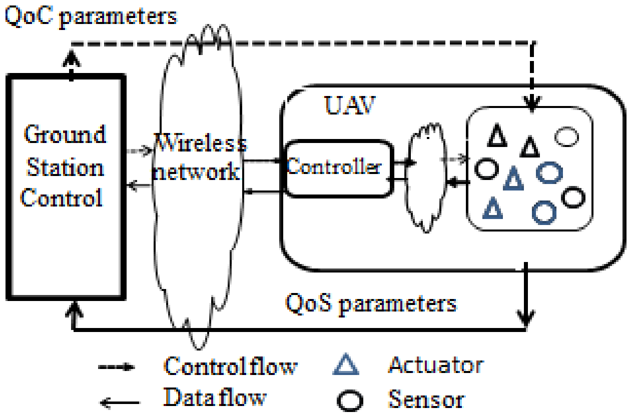

Figure 2 Co-design structure of Unmanned Ariel System QoS and QoC Requirements

Figure 2 shows the co-design structure of UAS. If large numbers of UAVs (swarms of UAVs) are under the control of the same ground station, then competition to access the channel increases and thus the effect of time delay will become severe for hard real time processes. The control commands generated will be sent to actuators, via the network medium. Ground station controller has computing speed and sufficient power backup. Nonetheless the controller placed in UAV is rather simple in its structure with resource constraints in terms of power and computing.

C. *QoS and QoC Requirements*

QoS is regarded as the capability of the network to provide assurance that service requirements of applications can be satisfied. Depending on the application, QoS in WNCS can be characterized by reliability, timeliness, robustness, availability, and security, among others. Some QoS parameters that are used to measure the degree of satisfaction of these services include throughput, delay, jitter, and packet loss rate [10]. For a UAV in mission mode, large delay in transmitting data from sensors to controllers and then from controllers to actuators and packet loss occurring during the course of these transmissions cannot be tolerated, while they may be acceptable for less time- critical tasks like health monitoring of the system. Priority fixing (service differentiation) is an essential component of QoS provisioning, and should be supported by communication protocol s [11]. QoC is defined as the performance delivered by each closed-loop operation, measured in several ways. In servo control problems - rise time, peak time, overshoot, and settling time are considered as QoC parameters. Related QoC parameters for frequency domain analysis are cross-over frequency, closed-loop bandwidth, amplitude margin, or phase margin. In regulatory control quadratic error cost function is taken as the QoC parameter. We have considered error cost function as QoC parameter for DMC, and settling time for Modified Smith predictor. The relation between QoC and QoS of network in the paradigm of NCS is described in [12].

Next, we propose the co-design Algorithms to improve the performance of wirelessly networked UAS.

D. *Proposed Algorithms for co-design*

TABLE I shows the proposed algorithms for co-design.

TABLE I ALGORITHMS FOR CO-DESIGN

```
Algorithm - A
if
        error cost of critical task > specified threshold
then
        choose appropriate protocol parameter values to
        the associated nodes
else
        keep the default values of protocol parameters
```

```
Algorithm - B
if
        wait time of control packet > specified wait time
then
        delay the sampling of low priority tasks without
        affecting the stability of closed loop
else
        keep the sample scheduling unchanged
```

What is new in the proposed approach is the feedback of QoC parameters of various tasks of different UAVs, like error cost, to the network coordinator. Network coordinator will select appropriate protocol parameter values meanwhile considering the priority status and error cost computed. Thus tasks with hard real time constraints can fulfill its mission within the specified time period over a network with enhanced QoS in terms of average wait time for sending packets and successful delivery of packets (reliability). This will improve its control performance in turn.

However, heavy network traffic load will degrade the network QoS obviously. What we propose is to delay the sample scheduling of soft real time processes in order to reduce the traffic and maintain minimum QoS of network to meet the time constrained tasks with satisfactory QoC values. In such a strategy, care should be taken while introducing the delay in sampling scheduling, so that it may not affect the stability of the closed loop. Assume a scenario of UAVs, having similar tasks with the same priority status. In that case either earliest deadline first scheduling or maximum error cost criteria can be adopted for the prioritization in packet transmission [13]. In this work error cost is considered for the prioritization. High priority tasks in the mission mode of aerial vehicle have been assigned with network protocol parameters values which results in lesser average wait time.

Applying these two algorithms of co-design, the impact of wait time delay due to the wireless medium can be mitigated to certain extent, would enhance the reliability and timeliness of critical tasks of UAVs.

The proposed controller design approaches are briefed in the next two sections.

III. MODIFIED SMITH PREDICTOR

A simple and common form of model based control that is effective for processes with long dead time is the Smith predictor. The Smith predictor structure utilizes a mathematical model of the process in inner feedback loop. The effects of modeling errors and load disturbances can be compensated using an outer loop. The use of the original Smith predictor control structure with integrating processes will result in an offset problem during certain load disturbance rejection scenarios. Modification can be applied to smith predictor, which is known to be Modified Smith Predictor, to ensure stability and zero steady state error.

A number of authors have proposed modifications to the Smith predictor structure to improve the regulator response of the compensated system and/or to reduce the effect due to process-model mismatch. Majhi and Atherton [14] suggest that improved responses may be obtained if appropriate dynamic terms are included in either the outer feedback loop (major loop) or the inner feedback loop (minor loop). The Modified Smith Predictor structure given in [14] is adopted here. Based on the assumption that the model used perfectly matches the plant dynamics, i.e., model transfer function $G_m = G$ (plant transfer function), and model time delay $T_{dm} = T_d$ (plant time delay), the set point and the load responses are given as follows:

$$y_{r(s)} = \frac{G G_{c1} e^{-T_d s}}{1 + G(G_{c1} + G_{c2})} \tag{4}$$

$$y_{l(s)} = \frac{G e^{-T_d s}[1 + G(G_{c1} + G_{c2} - G_{c1} e^{-T_d s})]}{[1 + G(G_{c1} + G_{c2})](1 + G G_{c3} e^{-T_d s})} \tag{5}$$

The controllers G_{c1}, G_{c2}, and G_{c3} are designed using P, PI or PID type. We have considered Proportional-Integral–Proportional-Derivative (PI-PD) modification for control system design [15]. The network time delay is considered as the part of system time delay.

IV. DYNAMIC MATRIX CONTROL

DMC was the first model predictive control algorithm developed [16] and has been widely accepted in the industrial world. Model Predictive Control (MPC) is used to deal with uncertainties in the system like parameter variations, time delay, nonlinearities etc. The basic idea of MPC controller is to iteratively use a process model of the physical system to predict and optimize future system behaviors. The various MPC algorithms only differ amongst themselves in the model used to represent the process, the noises and the cost function [17]. MPC and DMC used for the application of UAV control can be found in [18], [19] respectively.

The process model employed in the DMC here is the step response of the plant, while the disturbance is considered to be constant along the horizon (See [20] for details). The steps involved to obtain the predictions are as follows.

The step response model employed is:

$$y_{(t)} = y_0 + \sum_{i-1}^{N} g_i \Delta u_{(t-i)} \tag{6}$$

where g_i s are the sampled output values for the unit step input and $\Delta u_{(t)} = u_{(t)} - u_{(t-1)}$; y_0 can be taken as zero, N is the length of the truncated response. The predictor output will be

$$\hat{y}_{(t+k|t)} = \sum_{i=1}^{N} g_i \Delta u_{(t+k-i|t)} + f_{(t+k)} \tag{7}$$

where $f_{(t+k)}$ is the free response of the system, i.e., the part of the response that does not depend on the future control actions, and is given by:

$$f_{(t+k)} = y_{m(t)} + \sum_{i=1}^{N} g_{k+i} - g_i \Delta u_{(t-i)} \tag{8}$$

where $y_{m(t)}$ is the measured output. Now the prediction can be computed along the prediction horizon $(k = 1, \cdots, p)$ considering m control actions:

$$\hat{y}_{(t+k|t)} = \sum_{i=p-m+1}^{N} g_i \Delta u_{(t+p-i)} + f_{(t+k)} \tag{9}$$

Defining system's dynamic matrix G as

$$G = \begin{bmatrix} g_1 & 0 & \cdots & 0 \\ g_2 & g_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_m & g_{m-1} & \cdots & g_1 \\ \vdots & \vdots & \ddots & \vdots \\ g_p & g_{p-1} & \cdots & g_{p-m+1} \end{bmatrix} \tag{10}$$

It can be written as

$$\hat{y} = Gu + Fx_{(t)} \tag{11}$$

where $x_{(t)}$ is the state vector and is given by

$$x_{(t)}^{\mathrm{T}} = [y_{m(t)} \quad u_{(t-1)} \quad u_{(t-2)} \quad \cdots \quad u_{(t-N-1)}] \tag{12}$$

The objective of a DMC controller is to drive the output as close to the set-point as possible in a least-squares sense, with the possibility of the inclusion of a penalty term on the input moves. Therefore, the manipulated variables are selected to minimize a quadratic objective that can consider the minimization of future errors along with the control weight and error weight. The expression for the quadratic cost is given as follows:

$$J = \sum_{j=1}^{p} w\left(\hat{y}_{(t+j|t)} - y_{(t+j)}\right)^2 + \sum_{j=1}^{m} \lambda \Delta u_{(t+j-1)}^2 \tag{13}$$

Designing a DMC is challenging because of the number of tuning parameters that affect closed loop performance. The tuning parameters required to implement DMC include: the sample time, the prediction and control horizons, the model length, and the error and control weights. Various steps in the design of DMC are as given in **TABLE II**:

TABLE II DMC DESIGN STEPS

1) Specify the length of model; prediction and control horizons; error and control weights; set-point reference; and sampling time interval.
2) Find step response and obtain coefficients
3) Dynamic matrix is calculated (refer (10))
4) Calculate the control input
5) Predict the system output for free response and forced response (refer (7), (8) and (9))
6) Minimize the cost function J as shown in (13)
7) Calculate the future control input values and repeat the steps (5) and (6)

The onboard controller in UAV or the ground station controller transmits control packets through the wireless network. Network topology and parameters are influential factors of the network QoS in addition to the channel conditions. Tuning of IEEE 802.15.4 MAC parameters is given in the following Section.

V. IEEE 802.15.4 MAC PROTOCOL PARAMETER TUNING

The IEEE 802.15.4 standard [5] defines the PHY-layer and MAC layer specifications for low-rate, low power and low-cost for wireless connectivity. The protocol supports three networking topologies: star, peer-to-peer and cluster-tree. IEEE 802.15.4 MAC adopts carrier sense multiple access with collision avoidance (CSMA/CA) as the channel access mechanism. Hence, in an IEEE 802.15.4-based one-hop star network, the performance depends on the number of nodes competing for channel access and their packet generation rates as well as the configuration of IEEE 802.15.4 MAC parameters in the nodes.

In IEEE 802.15.4 standard, the channel access mechanism includes slotted CSMA/CA for the beacon-enabled mode and un-slotted CSMA/CA for the non-beacon-enabled mode, depending on network configurations [21], [22]. In both cases, the CSMA/CA algorithm is implemented based on back off periods, where one back off period shall be equal to a constant, i.e. *aUnit Back off Period*. A difference between the two cases is that, in the slotted CSMA/CA mechanism, the back off slots are aligned with the start of the beacon transmission, and the back off time is bounded by back off slot boundary. Contention window, defines the number of back off periods that need to be clear of activity before the transmission can start. The MAC parameters of the IEEE 802.15.4 considered here are the minimum value of the back off exponent (*macMinBE*), the maximum number of back offs (*macMaxCSMABackoffs*), Initial Retry window size, and the maximum number of retries (*macMaxFrameRetries*).

Each time a device needs to transmit data frames or control frames, it shall sense the medium for a random period. If the channel is sensed to be idle for a specified amount of time, the device is permitted to transmit its data. If the channel is busy, the device needs to wait for another random period before trying to access the channel again, and both number of back offs and back off exponent are incremented by 1. The tuning of the IEEE 802.15.4 MAC protocol for reliable and timely communication while minimizing the energy consumption can be formulated as a constrained optimization problem that every generic transmitting node solves:

$$\min E_{(\boldsymbol{Z})}$$

$$s.t. R_{(\boldsymbol{Z})} \geq R_{\min}$$

$$D_{(\boldsymbol{Z})} \leq D_{\max}$$

$$\boldsymbol{Z_0} \leq \boldsymbol{Z} \leq \boldsymbol{Z_m}$$

where $\boldsymbol{Z} =$ (macMinBE, macMaxCSMABackoffs, macMaxFrameRetries, InitialRetriyWindowSize)

The objective function $E(\mathbf{Z})$ is the total energy consumption of a node for transmitting packets plus energy for receiving the ACK at the node. The constraints are the probability of successful packet delivery (reliability) and average delay that a node experiences. $R_{\min}$ is the desired reliability, $D_{\max}$ is the desired maximum average delay and the constraint $\mathbf{Z}_0 \leq \mathbf{Z} \leq \mathbf{Z}_m$ captures the range of MAC parameters as specified in the standard. The energy, reliability and delay expressions are approximations as derived in [23]. The solution of the optimization problem gives the optimal MAC parameters that each node uses. Notice that the problem is combinatorial because the decision variables take on discrete values.

VI. SIMULATION RESULTS AND ANALYSIS

To tackle the time delay issues arising as a consequence of the use of wireless medium for transmitting control signals and measured outputs, the frequency response plots were obtained for system transfer function without and with time delay term added. How the time delay does affect the stability of the system is illustrated in the following example. Consider the pitch angular rate to elevator transfer function [24] for the UAV as given below.

$$G_{(s)} = \frac{-26s - 35.67}{s^2 + 6.4845s + 21.47} \tag{14}$$

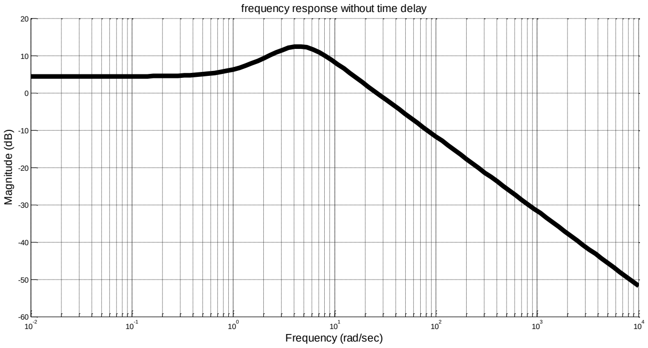

Figure 3 Frequency response of the system without time delay

Figure 3 shows the magnitude of frequency response with no time delay. The 3dB frequency is about 30Hz with a roll off of linear slope. **Figure 4** depicts the magnitudes of frequency responses with time delay ranging from 0.2 seconds to 0.8 seconds. Bandwidth of frequency responses reduces and the roll off with an oscillatory slope, indicating signs of instability. These figures describe how the stability gets affected and performance of system deteriorates with the increase in time delay. Simulation of Modified Smith predictor and DMC were carried out to examine how they cope with the effect of the network induced time delays.

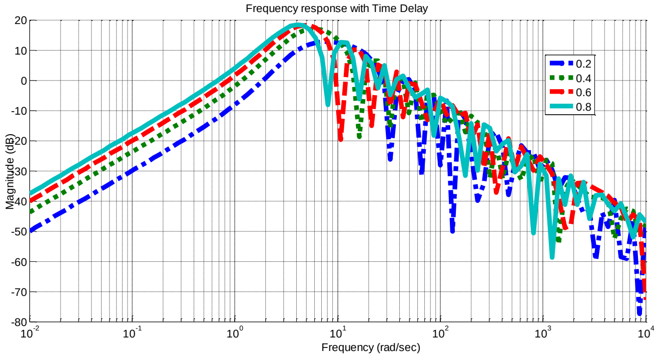

Figure 4 Frequency response of the system with time delay

A. *Modified Smith predictor*

Modified Smith predictor is the control strategy used for the systems with plant delay. Time delay to access wireless medium is in excess to the plant delay. The controller structure is designed using Simulink/MATLAB and it is described in **Figure 5**. Controller design Equations are listed as (16)-(18).

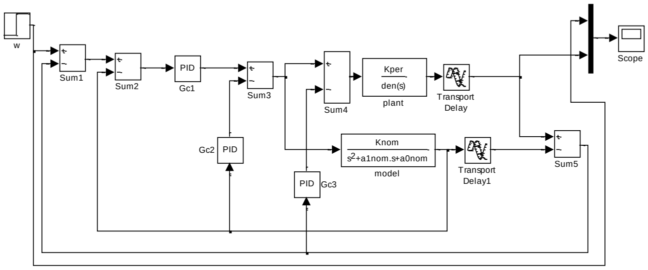

Figure 5 Modified Smith Predictor Simulink diagram

A UAV flight control system transfer function with time delay was considered as a controlled plant [25]. The same transfer function was assumed as a nominal system as well:

$$G_{(s)} = \frac{0.5}{10s^2 + 10.37s + 0.37} e^{-0.5s} \tag{15}$$

Time constants were supposed to be in seconds. The modified Smith predictor design by PI-PD was selected. The resultant controllers are in the form:

$$G_{c1(s)} = k_c\left(1 + \frac{1}{T_i s}\right) \tag{16}$$

$$G_{c2(s)} = T_d s + k_f \tag{17}$$

$$G_{c3(s)} = k_0 \tag{18}$$

with $k_c = 1$, $T_i = 0.1$, $T_d = 2.3848$, $k_f = 10.993$, and $k_0 = 0$.

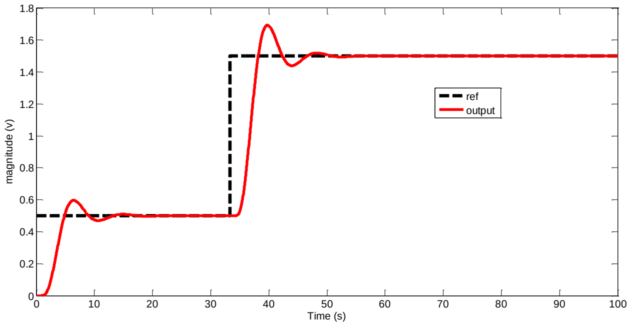

Figure 6 Modified Smith predictor output with a delay of 0.5 sec

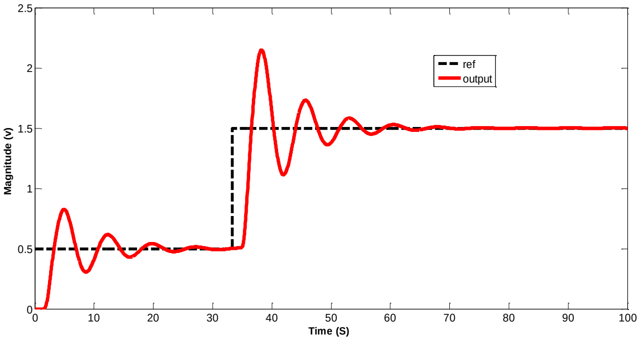

Figure 7 Modified Smith predictor output with a delay of 1 sec

Output was observed with respect to the step input applied as shown in **Figure 6**, with a time delay of 0.5second. The step response took a settling time of 15 seconds. With the time delay of 1 sec, the output response took a settling time of around 25 seconds. Observations are shown in **Figure 6** and **Figure 7**. Increasing the delay further, output response starts oscillating and system becomes unstable.

The following observations were made based on the results obtained: if the time delay is within the range of the plant delay, it will give reasonably good response to the step input applied. However, settling time increases considerably as the delay increases, and finally system becomes unstable.

B. *Dynamic Matrix Control*

We considered an aircraft pitch angle control loop transfer function [24] for the UAV as given below.

$$G_{(s)} = \frac{-26s - 35.67}{s^2 + 6.4845s + 21.47} \tag{19}$$

DMC was used for this LTI system and its parameters selected for the simulation were: sampling period T = 0.1 sec, time domain model length N = 50, predictive horizon length p = 10, receding horizon control step length m = 2. The error weight coefficient, w = 1, the controller weight coefficient = 0.1, and the set-point reference for output = 1. **Figure 8** and **Figure 9** show the plant outputs for DMC based MPC algorithm in MATLAB®, with and without time delay effect of the network. The plant output closely followed the set-point reference, when there is no network induced time delay. However, with a time delay of 0.5 second, the performance error is increased. If the delay is set to 1 sec and the performance is degraded again as the time delay increased further. However, we get a faster output response compared to Modified Smith predictor.

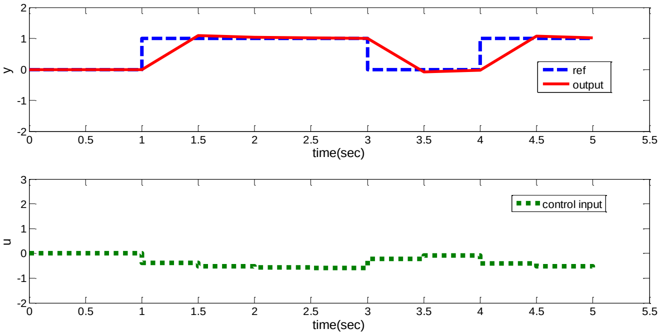

Figure 8 DMC based MPC output with a time delay of 0.5 sec

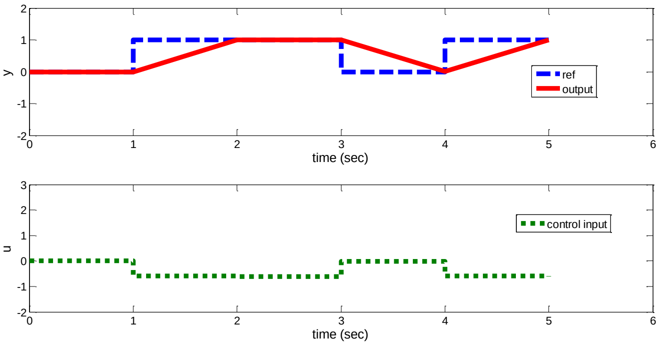

Figure 9 DMC based MPC output with a time delay of 1 sec

From the observations, a conclusion has been reached that the DMC performed well compared to Modified Smith Predictor in presence of time delays.

C. *IEEE 802.15.4 parameter tuning*

As we have seen, the system performance can be deteriorated, due to the time delay associated with the wireless network. Some of the tasks of UAV are very time-critical and maximum priority is given to such tasks. One or more parameters of IEEE 802.15.4 are modified in order to assign priority to reduce the adverse effects of time delays. **Figure 10** shows the average wait time versus varying offered load, with default value of parameters. Simulation of IEEE 802.15.4 physical and mac layer are done in MATLAB® , following the details given in [26]. Simulation parameters are optimized for minimum energy consumption.

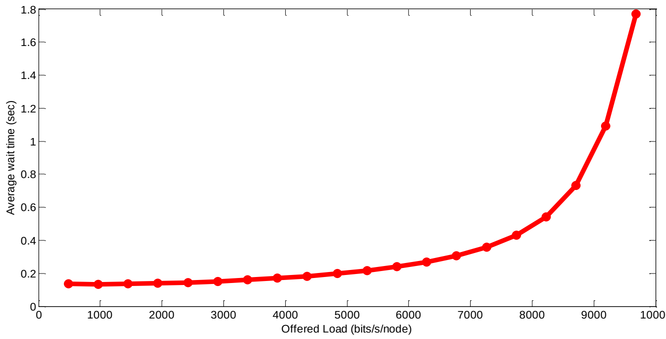

Figure 10 Average Wait Time Vs. Load for default set of parameter values

TABLE III PHY AND MAC FIXED PARAMETER VALUES USED FOR SIMULATION

PHY Layer Parameters	
Data Rate	20 kbits/sec
Bandwidth	30 KHz
Transmission power	5 dBm
Distance minimum	1 meter
Distance maximum	20 meter
MAC Layer Parameters	
Nodes	10
Buffer size	51 frames
Mac Frame size	100 bytes
a UnitBackoff Period	320µ sec
Mean propagation delay	222µ sec
MAC overhead	6 bytes
ACK frame	11 bytes
IFS	640µ sec

Network topology used is one hop star network, in beaconed mode. Fixed PHY and MAC parameter values selected for network simulation are shown in **TABLE III**. From the average wait time plots obtained through simulations, it is found varying with the parameter values like *macMaxFrameRetries*, *macCSMABackoffs* and *InitialRetryBackoffWindowSize*, *macMinBE*, etc. Simulation results are shown in **Figure 11** and **Figure 12** respectively. Observation from the obtained plot is that the priority can be assigned to the tasks by tuning appropriate parameter values of the network protocol.

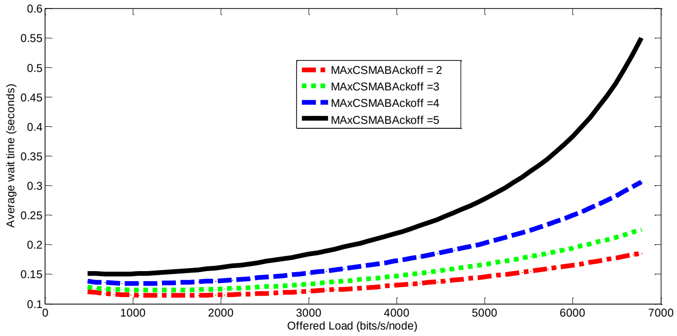

Figure 11 Average Wait Time Vs. Load: Max_Frame_Retries values = 2, 3, 4, 5

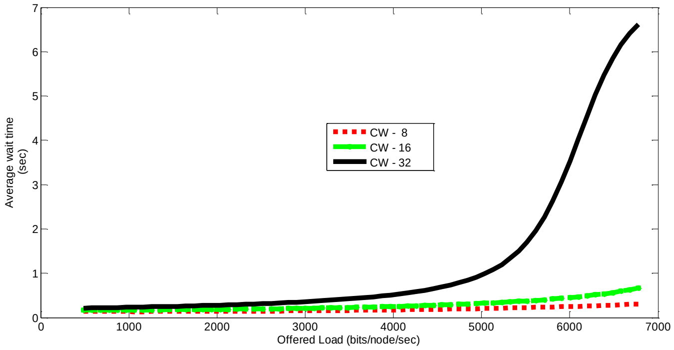

Figure 12 Average Wait Time Vs. Load: Initial Retry Backoff window size = 8, 16, 32

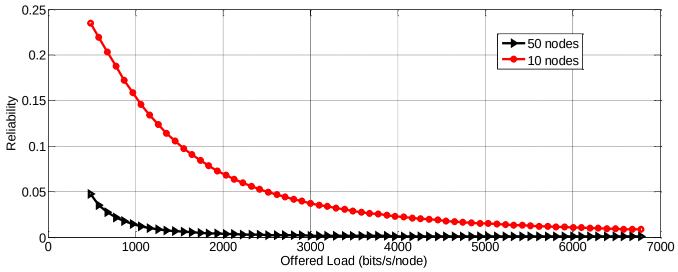

Figure 13 Reliability vs load for different network sizes

Reliability graph is plotted in **Figure 13**. A comparison of reliability (probability of successful packet transmission) for 10 nodes and 50 nodes can be found in the figure. As the number of nodes increases, reliability becomes lesser, and waiting time for channel access increases. Note that the variation in wait time is depending on the number of nodes, parameter values and probabilistic access of the channel for successful transmission of control and data packets.

D. Co-design of wireless networked UAS

As mentioned earlier, co-design approach is basically bootstrapping the design processes which are otherwise independent, and mostly one would inversely affect the other. So there is the need for finding an optimum combination of the design parameters of the control and network, for the problem being investigated. In the framework of co-design of NCS the average wait time of network can be reduced, and consequently QoC performance of the time-critical task can be improved. A simulation of joint design of network and controllers based on the proposed co-design algorithm has been performed on MATLAB®.

Simulation results of Algorithm – A is depicted in **Figure 14**. The solid line output shows the UAV process output in response to the DMC controller input, to follow the reference set point. The reference is shown with dashed line in **Figure 14(a)**. The dotted line shown in the same figure represents output for the time delayed system. If the error between reference and output is more than the specified threshold, a corresponding set of protocol parameter values have been selected so as to minimize the wait time for packet transmission (enhanced QoS). The dotted line graph in **Figure 14(b)** represents minimum average wait time, corresponding to the time delayed system output, whose performance error is larger (poor QoC). The default protocol parameter values are selected for the system output without delay and, its corresponding graph for average wait time is shown using solid line in **Figure 14(b)**. The difference in wait delay can be observed for varying network traffic load in bits/sec/node. When the network traffic load increases, wait time also increases. Reliability of wireless network graphs has been plotted in **Figure 14(c)**. Reliability, in terms of successful packet transmission, is higher for network with less wait time, which is represented with dotted line. The graph with solid line represents reliability for default set parameter values. UAV‘s time delayed output, which is modified, in response to the feedback of reduced network wait time, is shown with dotted line in **Figure 14(d)**. The Performance gets improved as the error cost is reduced.

Figure 15 describes the simulation results for the proposed Algorithm - B. If the network is congested, then the average wait time increases (poor QoS) and it is displayed using solid line in **Figure 15(b)**. This, in turn, will affect the performance of critical time or hard real processes.

In order to reduce the traffic, delay the sampling schedule of less critical processes whose output is represented with solid line plot in **Figure 15(a)**. Consequently the network performance improves and the corresponding wait time plot is given using dotted line in **Figure 15(b)**.

Then the output of critical time processes experience less wait time and it is plotted with dotted line in **Figure 15(a)**. Reliability graphs are plotted in **Figure 15(c)**. It is observed from the plots in **Figure 14** and **Figure 15** that the simulation results verified the proposed co-design algorithms.

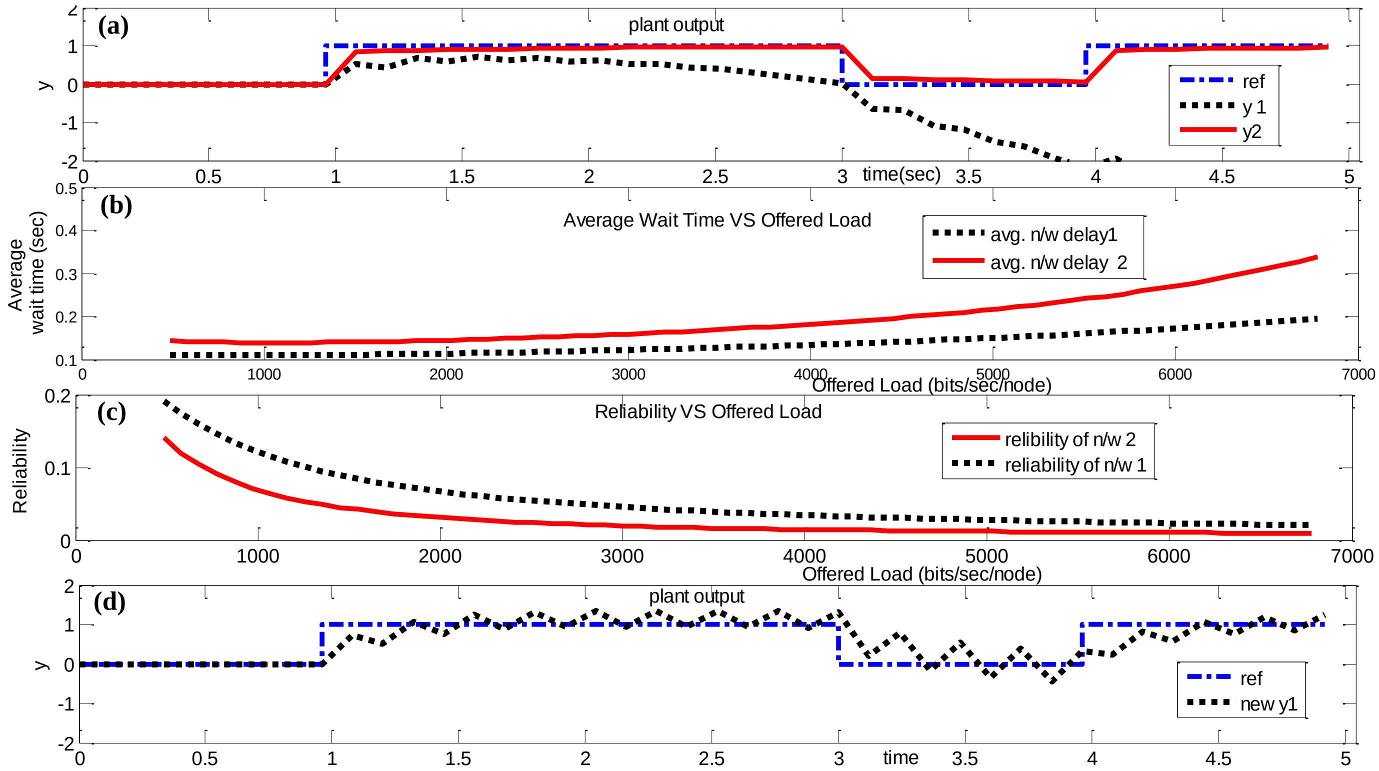

Figure 14 Network QoS varying with respect to QoC variation (Algorithm – A)

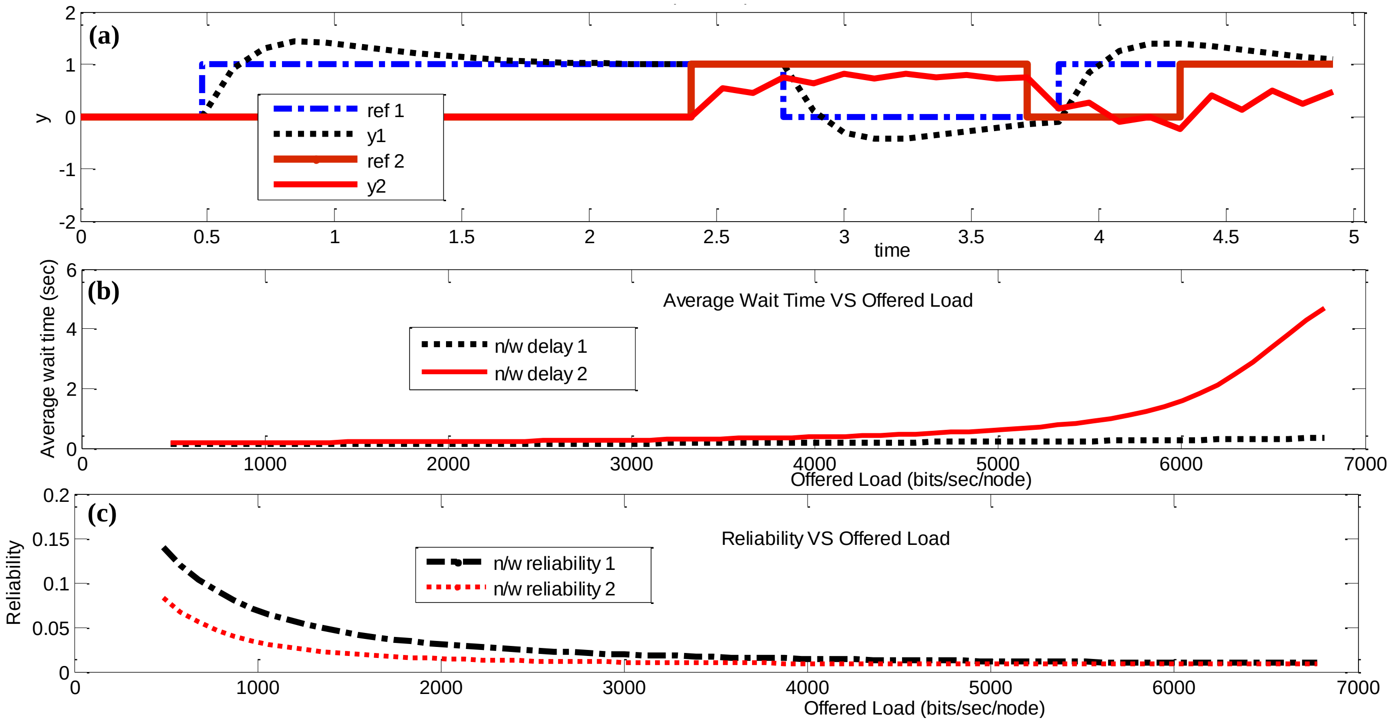

Figure 15 Delay in sampling with respect to network QoS values (Algorithm – B)

VII. CONCLUSION

A joint co-design approach for networked controlled system with an application to UAS is proposed for choosing the parameters of control and communication network. Dynamic Matrix Control and Modified Smith predictors have been considered as the controllers. The performance of the controllers has been tested with UAV transfer functions through simulations. Results showed an improved performance for DMC over Modified Smith predictor. The co-design algorithms proposed for UAV have been verified through the simulation. IEEE 802.15.4 is selected as the wireless network standard. The performance of the critical-time tasks, with high priority status assigned, and via the tuning of appropriate parameters of IEEE 802.15.4, gets improved despite poor network condition. Delaying the sampling schedule of less critical tasks also has the major role in improving the performance. Further research is needed for stability analysis when the delay is applied to the sampling schedule. More sophistication in the design of control is demanded while considering the plant/controller uncertainties along with random time delays of wireless channel. Future research shall be oriented in this direction.

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