Wireless Model Based Predictive Networked Control System Over Cooperative Wireless Network

Author1, *Member, IEEE,* Author2, *Member, IEEE,* and Author3, *Member, IEEE*

***Abstract*—Owing to their distributed architecture, networked control systems (NCS) are proven to be feasible in scenarios where a spatially distributed control system is required. Traditionally, such NCSs operate over real-time wired networks. Recently, in order to achieve the utmost flexibility, scalability, ease of deployment and maintainability, wireless networks such as IEEE 802.11 LANs are being preferred over dedicated wired networks. However, conventional NCSs with event-triggered controllers and actuators cannot operate over such general purpose wireless networks since the stability of the system is compromised due to unbounded delays and unpredictable packet losses that are typical in the wireless medium.**

Approaching the wireless networked control problem from two perspectives, this work introduces a novel wireless NCS and a realistic cooperative medium access control protocol implementation that work jointly to achieve decent control even under unbounded delay, bursts of packet loss and ambient wireless traffic. The proposed system is implemented and thoroughly evaluated on a dedicated test platform under numerous scenarios and is shown to be resilient to bursts of packet loss and ambient wireless traffic levels, which are intolerable for conventional NCSs while not being hindered by restraining assumptions of existing methods.

***Index Terms*—Distributed control, Predictive control, Access protocols, Cooperative systems**

I. INTRODUCTION

CONVENTIONAL Networked Control Systems (NCS) where event-triggered controllers and actuators of a distributed feedback control system operate in response to its time-triggered sensor nodes are suitable for scenarios that require spatial distribution. However, NCSs require dedicated real-time networks as total end to end latency of the system must be bounded. Regular networks can not satisfy this constraint due to random medium access latencies and multiple retransmissions caused by unpredictable transmission failures. Consequently, NCSs can not operate reliably over regular networks.

In order to overcome the problem of unpredictable delays and loss that the data packets of an NCS are subject to when operating over a regular network, in [1] and [2] authors propose to take the characteristics of the network into consideration during the design of the control system. However, this may not be a good design practice as the considered characteristics of the communication medium, such as traffic load and latency, can change during operation of the NCS. On the other hand, model predictive controllers are used in similar scenarios as given in [3] and [4], but these works either do not take the synchronization between the nodes into account or are not set up to be NCSs due to the fact that they rely on a direct-link between the sensor and controller and a transmission failure would inhibit future predictions.

As a remedy to addressed problems, Model Based Predictive Networked Control System (MBPNCS) proposed in [5] improves the performance of a NCS under variable time delays and packet losses by assuming standard NCS architecture with no requirement of direct links and a priori knowledge of the reference signal. MBPNCS, which operates over an ethernet LAN, employs a model based predictive controller which utilizes a model of the plant to predict control signals into the future and is shown to be operative under packet losses. However, the level of immunity MBPNCS provides against packet losses is only tested with a uniform packet loss model, which is not representative of true channel characteristics since packet losses are generally correlated and largely occur in bursts. Additionally, no experiments have been performed regarding the extent to which the traffic generated by other nodes on the network degrades the performance of the system.

Meanwhile, a truly flexible NCS must be wireless as dedicated cabling for communication may not be an option. In an attempt at making a given wireless network more suitable for Wireless NCSs (W-NCS), several polling and time division multiple access based medium access control (MAC) protocols are presented in [6]–[10]. However, as transmission failures caused by bursty and recurrent wireless channel errors directly increase the latency of a W-NCS's packets, improving the quality of the wireless channel is the first challenge of designing a W-NCS. In that respect, this work considers cooperative communications which have been shown to improve the quality of a wireless channel, specifically by employing the neighboring nodes of a wireless network as a set of distributed antennas [11]–[16].

Cooperative communications have its origins in relay channels which are initially studied in [17]. Subsequently, this matter has been approached from various perspectives: as [11]–[15] focus on the physical layer; [16], [18]–[22] mainly concentrate on the MAC layer along with some emphasis on cross-layer issues. Such systems require custom designed hardware which may not be widely available. IEEE 802.11 technology, on the other hand, has become the de facto standard for wireless LANs, and is also becoming popular in industrial environments. Hence, among these the Cooperative MAC (COMAC) protocol [21] is the most viable alternative due to its low complexity, IEEE 802.11 compatibility and its frame formats that can be derived from IEEE 802.11.

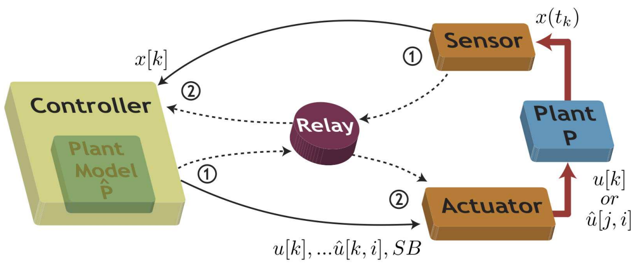

Fig. 1. Overall architecture of W-MBPNCS and cooperation.

Nonetheless, these works primarily emphasize that cooperation between the nodes either results in higher throughput from the perspective of ad-hoc multimedia communication or reduced power consumption from the perspective of wireless sensor networks. Although [10], [23] examine the effects of cooperative communications on the reliability and latency of data packets from the perspective of wireless sensor networks, cooperation is seldom approached from the perspective of low-latency high-performance networks. Cooperative communications can indeed make a given wireless network more suitable for delay-sensitive applications by decreasing the number of required re-transmissions in a fading channel.

In this work, a novel Wireless MBPNCS (W-MBPNCS) [24] and a faithful implementation of the COMAC protocol are presented which work jointly to solve the problem of operating an NCS over a wireless network. W-MBPNCS is a time-triggered wireless networked control system, which is resilient to wireless channel impairments such as unbounded packet latencies and unpredictable packet losses. As W-MBPNCS approaches the wireless control problem from the control perspective, COMAC focuses on the physical and MAC layers of the wireless communication protocol. Through cooperation of the neighboring nodes, COMAC achieves higher packet success rates improving controller performance even further under adverse wireless channel conditions. The rest of the paper is organized as follows: The next section provides an overview of the system and some background on the wireless channel and the control algorithm. Section III deals with W-MBPNCS over COMAC in detail and Section IV presents the results of the experiments. Finally, Section V discusses the results of the experiments and concludes.

II. SYSTEM ARCHITECTURE AND BACKGROUND

A typical W-MBPNCS operating over COMAC comprises 5 components as given in Fig. 1: the sensor node, the controller node, which also contains the model $\hat{P}$ of the plant, the actuator node, the actual plant P and the relay.

During the operation of W-MBPNCS, the sensor periodically reads plant outputs and communicates this data to the controller over the wireless network. In addition to calculating the control signal, the controller also predicts an additional number of control signals into the future using $\hat{P}$. Upon retrieval of controller packets, the actuator applies appropriate control signals to the plant.

W-MBPNCS supports two types of wireless access: IEEE 802.11 with modified MAC parameters and IEEE 802.11 based COMAC. When W-MBPNCS uses the modified IEEE 802.11 MAC the nodes communicate directly with each other. When COMAC is utilized the nodes communicate with each other cooperatively in two stages: In *stage 1*, the source node disseminates a packet to the destination node which is also overheard by the relay. In *stage 2*, relay cooperates with source in transmission of the packet to its destination. Diversity receiver at the destination node combines these two copies of the packet significantly increasing chances of successful reception due to improved signal to noise ratio (SNR). In this architecture, the source node can be the sensor or the controller and the destination node can be the controller or the actuator as indicated by the arrows in Fig. 1. Relay node can be any neighboring node that can overhear and be heard by W-MBPNCS nodes.

A. *Wireless Access*

IEEE 802.11 MAC uses a contention based medium access mechanism called *Distributed Coordination Function* (DCF) which is responsible for avoiding collisions and resolving them when they occur as multiple wireless nodes try to transmit simultaneously. Functionality of DCF primarily depends on 5 key parameters: network allocation vector (NAV), DCF interframe space ($DIFS$) and contention window (CW) chosen from the interval $[CW_{min}, CW_{max}]$. Each node has a NAV, which indicates the remaining busy period of the channel as derived from overheard frames and a backoff timer. Using DCF, a node attempts to transmit only if it thinks the medium is free as indicated by a zero NAV and a channel that remains free throughout the DIFS interval. If the medium is busy, the node defers transmission until the next time the channel is free; otherwise waits for an additional amount of time determined by its backoff timer. If the channel remains free until its backoff timer expires, the node begins transmission; if not, it defers transmission until the next time the channel is free. Each successful transmission is concluded with an acknowledgment. Thus, any node which misses its acknowledgement updates its CW parameter and reloads its backoff timer accordingly before each retransmission. COMAC also uses the same DCF based medium access mechanism as IEEE 802.11.

The above mentioned parameters are updated as follows: Whenever the medium is found to be busy, the backoff timer is reset according to $Random() \times slot\_time$. `Random()` is a pseudo-random integer from a uniform distribution over the interval $[0, CW]$. CW initially equals CW_{min} and is incremented exponentially ($CW = 2^{retries} - 1$) before each retry until it reaches CW_{max}.

B. *Wireless Channel*

Characteristics of a wireless channel is closely coupled to its surroundings and remain correlated for some time after a change [25]. Thus, transmission errors on the wireless channel occur typically in bursts followed by practically error-free periods rather than occurring completely randomly. Block fading occurs when the duration and separation of these error bursts are large relative to the delay constraint of the channel, duration in which the channel must preserve its characteristics for satisfactory operation. Fast fading, on the other hand, occurs when the characteristics of the channel change faster than the delay constraint of the channel. In this work, the performance of W-MBPNCS is evaluated considering both block fading via a bursty channel errors model and fast fading via an SNR based Rayleigh fading model. These two models are selected since they are not only realistic but easy to implement as well.

1) Block Fading and Bursty Channel Errors: The bursty error characteristics of the wireless channel under block fading can be best modeled by the Gilbert/Elliot channel model [26]. At any given time, the characteristics of the emulated channel are determined by the *good* and *bad* states of the model, in which packets are lost according to packet loss probabilities P^g_{loss} and P^b_{loss} respectively. The next state of the channel is determined by state transition probabilities P_{gb} and P_{bg} after each packet. Since state transition probabilities are typically small, the channel state remains unchanged for some time after a transition imitating bursts of packet loss when the model is in the *bad* state and periods of almost error free transmission when the model is in the *good* state. The packet loss and transition probabilities have been obtained in [27] considering channel measurements in an industrial setting.

2) Fast Fading: Rayleigh Fading: In an industrial setting with numerous obstacles and no direct line of sight between the transmitter and the receiver, multipath fading causes rapid fluctuations in the received signal strength. These fluctuations can be modeled with the Rayleigh distribution [25], [28] which is essentially an exponential distribution with mean $\bar{P}_{rx}$, the average received signal power. For a distance aware Rayleigh fading model, this work uses an exponential random variable (Y) scaled by P_t/d^α where P_t is transmission power, d is the distance between the transmitting and receiving nodes and α is the path loss exponent.

C. The Plant and The Control Algorithm

To evaluate the performance of W-MBPNCS, this work aims position control of a DC motor with the following linear approximation:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -b/J & K_t/J \\ 0 & -K_v/L & -R/L \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix}$$
$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix}, x = \begin{bmatrix} \theta \\ \dot{\theta} \\ i \end{bmatrix} \tag{1}$$

where b is the damping coefficient, J is the rotor moment of inertia, K_t is the torque constant, K_v is the speed constant, L is the terminal inductance, R is the terminal resistance, θ is the position, $\dot{\theta}$ is the speed and i is the current of the motor. Once the relevant parameters of the plant are obtained and a discrete-time model is prepared for 100 Hz sampling rate, a full state feedback controller for position control is implemented as $u[k] = G_r r[k] - Kx[k]$. A Luenberger observer [29] which estimates motor speed and current from measured motor position is obtained from a full state observer (Eq. 2) by selecting the observer gain K_o such that $\bar{C}K_o = I$ where $\bar{A}$, $\bar{B}$, $\bar{C}$, $\bar{D}$ are discretized versions of A, B, C, D, $\hat{x}$ is the estimated plant state.

$$\begin{aligned} \hat{x}[k] &= \bar{A}\hat{x}[k-1] + \bar{B}u[k-1] \\ &\quad + K_o(y[k] - \bar{C}(\bar{A}\hat{x}[k-1] + \bar{B}u[k-1])) \end{aligned} \tag{2}$$

III. WIRELESS MODEL BASED PREDICTIVE NETWORKED CONTROL SYSTEM OVER COOPERATIVE MEDIUM ACCESS CONTROL PROTOCOL

W-MBPNCS is a time-triggered discrete-time control system specifically designed to provide resilience to indeterministic bursty packet losses observed in the wireless channel [24]. In order to minimize packet delays and losses due to collisions caused by ambient wireless traffic, W-MBPNCS takes advantage of modified medium access control parameters for higher priority medium access. Relative packet deadlines defined on each node of the system introduce an upper bound on packet latency by discarding late arriving packets, even though the network does not provide such a bound. As a means to tolerate intermittent packet losses, the controller of the W-MBPNCS employs a model of the plant to be used in prediction of future control signals which are appropriately applied to the plant by the actuator state machine. Additionally, improvement in the wireless link quality provided by the COMAC protocol enhances the control performance of W-MBPNCS even further under severely fading channels.

A. Resilience to Ambient Wireless Traffic

Wireless channel is of broadcast nature, and ambient wireless traffic may interfere with a W-MBPNCS node's transmission causing its packet to be lost. Using DCF, the node has to wait for a random amount of time before each retransmission attempt increasing the latency of the packet. Since DCF is stochastic in nature with no upper bound on medium access latency, W-MBPNCS's packets may suffer significantly high latencies under ambient wireless traffic. As a remedy to this problem, CW_{max} is decreased in order to limit the packet latency variance in case of collisions and $DIFS$ and CW_{min} are decreased for higher medium access priority and lower packet latencies as given in [24].

B. Per-node Relative Packet Deadlines

Modified MAC parameters shrink the latency of W-MBPNCS packets under ambient wireless traffic to some extent but the packets can still be delayed due to other wireless channel problems such as fading. This delay can be so long that the packets' payloads may be irrelevant by the time they arrive at their destinations. In order to introduce an upper bound on packet latency and filter out late packets, W-MBPNCS nodes employ per-node relative packet deadlines as follows: The sensor samples, appends a time stamp to and transmits the plant outputs at a period of T to the controller. The controller operates with a phase shift with respect to the sensor (typical network delay + $T/10$ in this case) introducing a relative deadline for sensor packets. Details of the initialization mechanism used to approximate this behavior

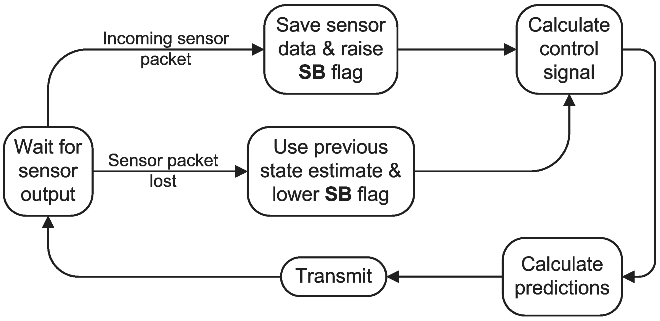

Fig. 2. Operation of the controller node.

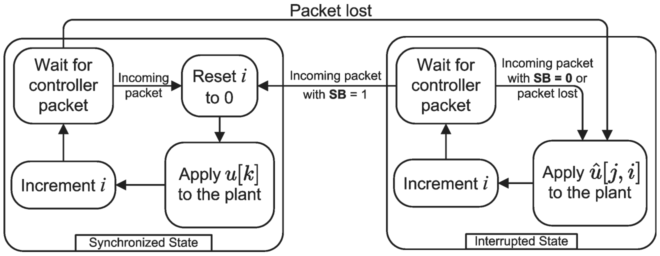

Fig. 3. Operation of the actuator node.

can be found in [24]. Following initialization, the controller node checks the time stamps of the incoming packets and ignores any packets that fail to meet their deadlines, effectively reducing the unbounded packet latency to packet loss. The initialization and the time stamp mechanisms also work in the same way between the controller and the actuator.

C. Model Based Predictive Controller and Actuator State Machine

As per-node relative packet deadlines reduce unbounded packet latency to packet loss, the deteriorating effect of lost packets on the controller performance is mitigated through the control signal predictions of W-MBPNCS's model based predictive controller. Besides calculating the control signal $u[k]$ for the current time step, the controller node (Figs. 1, 2) also predicts n future control signal estimates ($\hat{u}[k,i], \{i : [1,n]\}$) using output and state predictions ($\hat{x}[k,i], \{i : [1,n]\}$) of the plant model $\hat{P}$ as given in [5]. The source of the k^{th} controller packet can be either the incoming sensor data $x[k]$, or the first state estimation produced at the previous time step $\hat{x}[k-1,1]$. To able to differentiate such cases, a *sensor based* (*SB*) flag is also stored in the controller packet because in the latter case, the controller packet is valid only if $u[k-1]$ is also applied to P implying that the $(k-1)^{st}$ controller packet is not lost. If a controller packet is lost, further control signals sent by the controller become obsolete until the next time the controller is *synchronized* with the plant by receiving a sensor packet and successfully sending its *sensor based* calculations to the actuator.

In order to cope with this synchronization issue between $\hat{P}$ and P, the actuator embodies a state machine (Fig. 3) with two states corresponding to instants when $\hat{P}$ and P are synchronized (*synchronized state*) and out of synchronization (*interrupted state*) as in [5]. When the actuator is in the *synchronized state*, $u[k]$ of each packet is applied to the plant regardless of the condition of the *SB* flag until a controller packet is lost and actuator state machine makes a transition to the *interrupted state*. In the *interrupted state*, incoming controller packets are ignored and predictions of the last controller packet received in the *synchronized state* are applied to the plant in a consecutive manner ($\hat{u}[j,i]$, { i: [1, n] }) until a *sensor based* controller packet is received upon which the actuator state machine returns to the *synchronized state*. If the actuator runs out of predictions in the *interrupted state*, it keeps applying the last control signal estimate $\hat{u}[j,n]$ to P until a *sensor based* controller packet is received.

When there is no packet loss between its nodes, W-MBPNCS acts as a regular discrete-time control system. However, during periods of packet loss, P receives control signals based on $\hat{P}$'s state estimates instead of its own actual states. Thus, at each consecutive packet loss, these control signal estimates deviate from actual control signals as $\hat{P}$'s state estimates deviate from P's actual states due to modeling errors. Consequently, during such intervals P's stability depends on the length of the packet loss burst and modeling errors in $\hat{P}$. An analysis of the stability conditions for MBPNCS during bursts of packet loss which is directly applicable to W-MBPNCS can be found in [30]. Nevertheless, the number of predictions n is chosen as 50 which is a suitable value for maintaining the stability of the W-MBPNCS platform during experiments.

D. COMAC Protocol

Countermeasures discussed so far all try to mitigate the negative effects of various wireless channel impairments on the controller performance. COMAC, on the other hand, aims to achieve superior wireless link quality when compared to non-cooperative IEEE 802.11 by utilizing Maximal Ratio Combining (MRC) implemented in the diversity receivers of the cooperating nodes [21]. MRC is a diversity combining technique for mitigating the effects of fading [28]. In an optimal MRC, signals received at the branches of an M-branch linear combiner are combined in such a way that output SNR is the sum of SNR's of individual branches. This way, the impact of a faded independent signal path is diminished through utilization of the signal power received at other branches and controller performance of W-MBPNCS is enhanced. For the sake of brevity, this work considers only the case where the source always requests cooperation from the same relay and that particular relay is always available for cooperation. Interested reader is referred to [22] in which authors introduce an efficient distributed relay actuation mechanism for COMAC.

COMAC uses five special frames which are distinguished from regular IEEE 802.11 frames by their modified reserved frame control bits. A cooperative communication is initiated by a C-RTS (request to send) frame sent from source to destination reserving the medium for one COMAC exchange. In this architecture, the source can be either the controller or the sensor, the destination can be either the controller or the actuator and the relay can be any neighboring node.

After receiving the C-RTS frame, destination replies with a C-CTS (clear to send) frame. Overhearing the C-RTS and C-CTS frames, relay sends an ACO (available to cooperate) frame to source and the two stage cooperative communication commences as given in Fig. 1: In stage-1, source disseminates the C-DATA-I frame to destination which is also overheard and decoded by relay. In stage-2 source and relay send the C-DATA-II frame, which holds the same payload as C-DATA-I, simultaneously to destination. After combining and successfully decoding the received data packets, destination ends the cooperative transaction with a *C-ACK* frame. It is this final step where COMAC enhances the quality of an otherwise poor wireless link through the cooperation of neighboring nodes.

IV. EXPERIMENTAL RESULTS

A. Test Platform

The platform on which W-MBPNCS and COMAC are realized is mainly made of an Advantech PCM-9584 industrial computer board, a CNET CWP-854 wireless NIC, a Mesa 4i30 quadrature counter daughter board, a Kontron 104-ADIO12-8 ADC/DAC daughter board and a Maxon RE-35 DC motor. Debian GNU/Linux distribution is used as the operating system along with the open source wireless NIC drivers developed by the rt2x00 project and Xenomai real-time development framework. COMAC implementation and Rayleigh fading model is realized inside the rt2x00 kernel modules whereas W-MBPNCS tasks and the bursty channel model are implemented as real-time user-space Xenomai tasks.

In order to be able to realize the COMAC protocol faithfully various low-level issues are addressed: frame filters, NAV and medium access behavior of the NIC are modified to enable reception of and response to overheard frames, automatic acknowledgement mechanism is suspended to ensure proper protocol flow and various timeouts, duplicate detection and recovery mechanisms are implemented for robustness. At the final stage of the COMAC protocol, C-DATA-I and C-DATA-II frames are transmitted simultaneously by source and relay and are decoded using MRC at destination. As this is not possible to achieve using commercial-off-the-shelf hardware, in the implementation C-DATA-II frame is transmitted only by relay whereas source remains silent during this period and MRC is emulated in software. This is the only significant difference between COMAC implementation and its proposed counterpart making it one of the most realistic soft-MAC implementations.

In order to reduce the number of computers required, sensor and actuator nodes of the system are colocated in the same computer (sensor/actuator). Although this simplification does not alter the behavior of the W-MBPNCS as these nodes never directly interact, link qualities of the sensor and the actuator nodes become correlated when COMAC is utilized as both nodes share the same kernel module which also hosts the channel emulation. Nevertheless, this enforced assumption is both reasonable as sensors and actuators are typically close to each other and beneficial as it simplifies the experiment scenarios. For the experiments with ambient wireless traffic, a third node is placed in the middle of two other nodes for traffic generation. For the experiments with COMAC, this node is utilized as the relay node. During test runs an automated test method is used in order to eliminate human error.

B. Controller Performance using Modified IEEE 802.11 MAC Parameters

In the experiments conducted, mainly the performance of the W-MBPNCS is compared with the performance of a conventional W-NCS under block fading and ambient wireless traffic. W-NCS implements the control algorithm with per-node relative packet deadlines but lacks the model based predictive functionality; hence keeps the plant input unchanged in case of lost packets. Note that, both systems use the IEEE 802.11 (2 Mbps with QPSK) as the wireless access scheme.

In order to evaluate the effects of packet loss in a controlled way, the bursty channel model is implemented in the nodes of systems. The parameters of the model ($P_{gb} = 0.0196$, $P_{bg} = 0.282$, $P^{g}_{loss} = 0$, $P^{b}_{loss} = 1$) are derived from the results presented in [27] which were obtained in an industrial setting.

As a means to observe the effect of ambient wireless traffic and the improvement provided by modified MAC parameters, tests both with and without traffic (750 UDP packets/s with 50 bytes of payload and duration of $648\mu s$) using both stock ($DIFS = 50, CW_{min} = 31, CW_{max} = 1023$) and modified MAC parameters ($DIFS = 30, CW_{min} = 0, CW_{max} = 3$) are conducted. Size of the traffic packets' payload is chosen such that their transmission duration is less than the $1\ ms$ relative packet deadline between the nodes of the system. This way, the main reason of packet loss will be the backoff mechanism of 802.11 and not the duration of the traffic packets. MAC parameters of the traffic generator are left at their stock settings and no packet loss model is employed in the traffic generator for maximum interference.

Controller performance of an NCS is determined by its percentage root mean square of error ($eRMS$) given by

$$Percentage\ eRMS = \sqrt{\frac{\sum_{k=1}^{n}(\theta[k] - r[k])^2}{\sum_{k=1}^{n} r[k]^2}} \qquad (3)$$

where $r[k]$ and $\theta[k]$ are reference and plant positions at time step k. In Figs. 4, 5 percentage $eRMS$ averages of both systems taken over 10 identical runs of 80 experiments, each 30 seconds long, are plotted against the mean packet loss rate ($\overline{PLR_m}$) of the bursty channel model. $\overline{PLR_m}$ is the weighted average of P^{g}_{loss} and P^{b}_{loss} with respect to steady state probabilities of the model being in a given state. Results of experiments with ambient wireless traffic are presented as dashed lines in the figures. The same reference signal, a 0.5 Hz step input with an amplitude of *2 radians*, is used in all experiments except for the last experiment (Fig. 6) where a sawtooth reference with a slope of *4 radians/s* is used.

In the first test (Fig. 4), controller performance of the conventional W-NCS is evaluated under bursts of packet loss when using standard and modified MAC parameters both with and without ambient wireless traffic. P^{g}_{loss} of the bursty channel model is swept from 0% to 45% at 5% increments to imitate non-ideal channel characteristics in the good state. When there

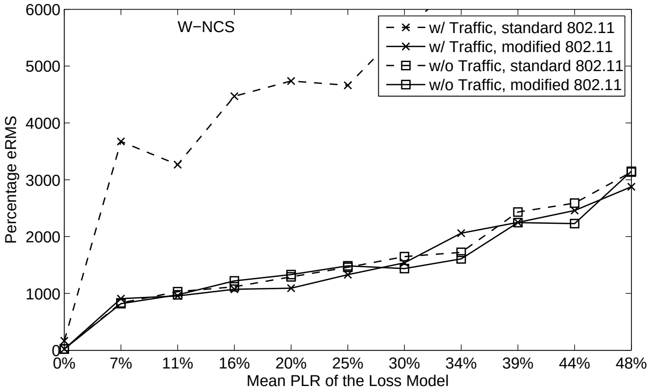

Fig. 4. Controller performance of the conventional W-NCS over IEEE 802.11 under bursts of packet loss, using standard and modified MAC, with and without ambient wireless traffic

is no traffic, W-NCS is stable only when the channel model is inactive and becomes unstable with a percentage $eRMS$ of 800% under bursty packet loss even at 7% $\overline{PLR}_m$. W-NCS with standard MAC parameters can not operate under ambient wireless traffic as its percentage $eRMS$ exceeds 160% even at 0% $\overline{PLR}_m$. When the experiment is repeated using modified MAC parameters, performance of W-NCS is insensitive to wireless traffic, but it remains inoperative under bursty packet losses.

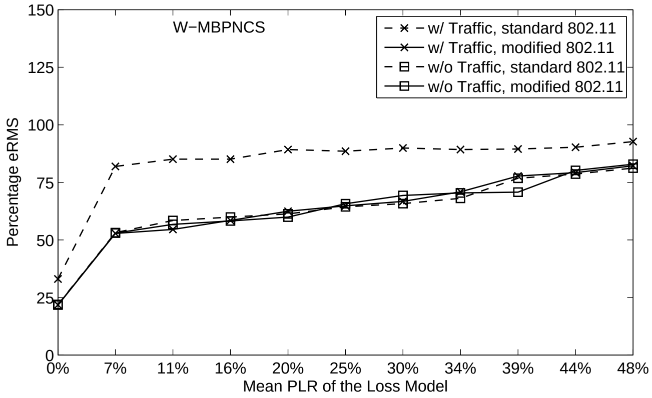

Fig. 5. Controller performance of W-MBPNCS over IEEE 802.11 under bursts of packet loss, using standard and modified MAC, with and without ambient wireless traffic

In the second test (Fig. 5) the scenarios of the first test are repeated for W-MBPNCS. When there is no traffic, percentage $eRMS$ of W-MBPNCS is 54% at 7% $\overline{PLR}_m$ and never exceeds 85%. Under ambient wireless traffic performance of W-MBPNCS with standard MAC parameters degrades by at least 15%, nevertheless it still remains stable and clearly outperforms the conventional W-NCS. When modified MAC parameters are used, the performance degradation of W-MBPNCS under ambient wireless traffic is reduced by almost 100%.

Finally, a time plot of plant output (motor position) obtained in response to a sawtooth reference signal with a slope of 4 radians/s under bursty packet loss ($\overline{PLR}_m = 7\%$) and no ambient wireless traffic is given in Fig. 6. As the conventional W-NCSs instability manifests itself as spikes in plant output and a percentage $eRMS$ of 726%, W-MBPNCS remains stable with a percentage $eRMS$ of 77% albeit with some insensitivity to the tracking of the reference input due to loss of communication between its nodes.

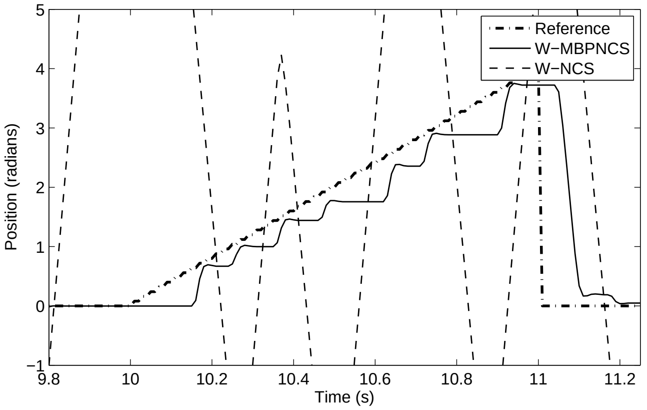

Fig. 6. Sawtooth reference vs. plant output using IEEE 802.11 MAC under bursts of packet loss

C. Controller Performance using COMAC

In this section the performance of W-MBPNCS is evaluated using both COMAC and standard IEEE 802.11 MAC protocols over a Rayleigh fading channel ($P_t = 1\ mW$, $\alpha = 4$) for different node distributions along a straight line. Rayleigh fading model is used to emulate severe wireless channel conditions and distance between the controller and sensor/actuator is considered to observe the effect of path loss. In experiments with COMAC, position of the relay is also considered to observe its effect on COMAC's performance. IEEE 802.11 parameters are left at their standard values since ambient traffic is not considered in this section.

Five sets of 10 scenarios are considered for experiments with COMAC. Within each set, the relative position of relay with respect to other nodes is constant and the distance d between the controller and the sensor/actuator nodes are swept from $40\ m$ to $85\ m$ at $5\ m$ increments. In the first set, relay is positioned between controller and sensor/actuator so that the ratio d_R of the distance between relay and controller with respect to the distance between controller and sensor/actuator is $1/6$ and d_R is incremented by $1/6$ for each set reaching $5/6$ at the fifth set. For the experiments with IEEE 802.11, as there is no relay, a single set of 10 scenarios is considered where d between the controller and sensor/actuator is swept from $40\ m$ to $85\ m$ at $5\ m$ increments. Results presented in the following are averages of 10 identical runs of each experiment.

Fig. 7 illustrates how COMAC diminishes both mean and maximum packet loss burst lengths both of which are very critical to the controller performance of an NCS. Minimums are not shown in the error bars as they are always zero. When the nodes communicate using IEEE 802.11, mean packet loss burst length at the controller is 5 when d is $70\ m$ and exceeds 20 when d reaches $85\ m$, whereas when COMAC is utilized, it always remains below 2 when the relay is in the middle

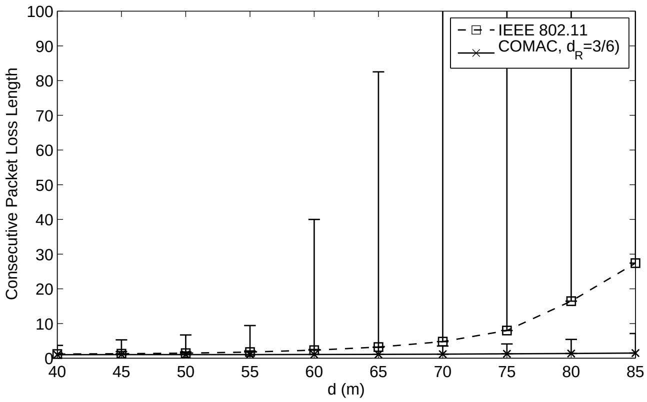

Fig. 7. Mean and maximum lengths of consecutive packet losses at the controller vs. d using both COMAC and IEEE 802.11 MAC

and never exceeds 6 for other cases. More importantly, when nodes communicate using IEEE 802.11 maximum packet loss burst length at the controller increases superlinearly with d and exceeds 40 when d is $60\ m$. For a 100 Hz control system such as the one used in this work, this corresponds to 0.4 seconds of insensitivity to reference input which renders the system unusable for most cases. On the other hand, variance in packet loss burst length is greatly reduced when COMAC is used and maximum packet loss burst length at controller never exceeds 8 when relay is in the middle.

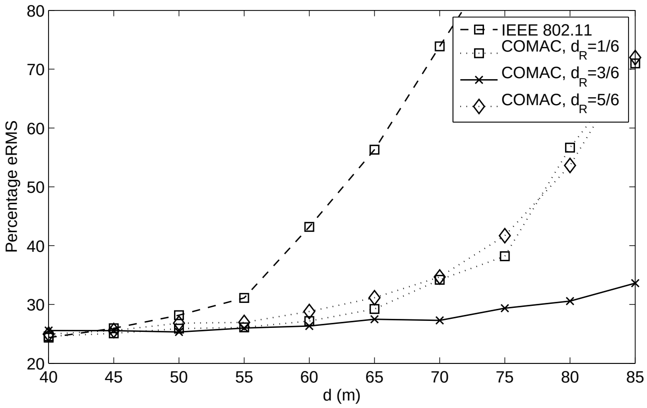

Fig. 8. Controller performance of W-MBPNCS over COMAC under Rayleigh fading vs. d

Fig. 8 demonstrates the effect of both MAC protocols on the performance of W-MBPNCS under various scenarios. When the nodes use IEEE 802.11, controller performance degrades as d increases and percentage $eRMS$ exceeds 70% for d greater than $70\ m$. On the other hand, when COMAC is used and the relay is in the middle, controller performance is almost independent of d up to $85\ m$ as percentage $eRMS$ remains below 35% in all scenarios. Nevertheless, W-MBPNCS' performance considerably depends on relay's position and degrades when relay is not in the middle. This can be explained as follows: When relay is closer to source, chances of initiating a cooperation is higher; but as both source and relay are away from destination, SNR's of C-DATA-I and C-DATA-II at destination are lower decreasing chances of successful cooperation. When relay is closer to destination, chances of initiating a cooperation is lower since SNR's of C-RTS and ACO frames exchanged between relay and source are lower. Since W-MBPNCS is a closed loop system whose nodes act both as source and destination, both cases cause a degradation in controller performance due to increased packet loss and best controller performance is achieved when relay is in the middle as given in Fig. 9.

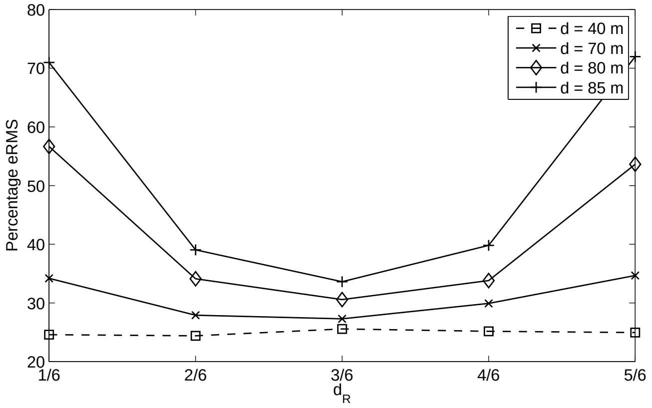

Fig. 9. Controller performance of W-MBPNCS over COMAC under Rayleigh fading vs. d_R

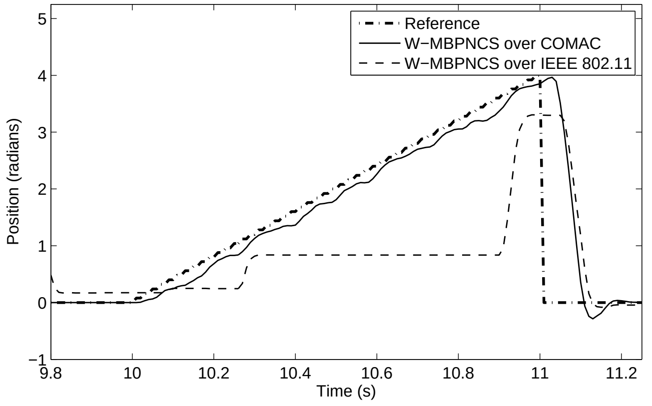

Fig. 10. Sawtooth reference vs. plant output using COMAC under Rayleigh Fading

Finally, Fig. 10 illustrates how W-MBPNCS benefits from COMAC when relay is in the middle, d is $70\ m$ and a sawtooth reference signal with a slope of 4 radians/s is applied to the controller. When W-MBPNCS nodes communicate using IEEE 802.11 the system remains insensitive to the changing reference during bursts of packet loss, whereas the plant follows the reference closely when COMAC is utilized.

V. CONCLUSION

W-MBPNCS presented in this work is a time-triggered wireless networked control system, which operates over a wireless ad-hoc network. W-MBPNCS employs modified medium access control (MAC) parameters, per-node relative packet deadlines, a model based predictive controller and an actuator state machine to reduce unbounded packet latency to tolerable packet loss. COMAC, on the other hand, improves the controller performance even further by enabling reliable and timely data transmission even under severe wireless channel conditions.

Aiming position control of a DC motor, the performance of the proposed W-MBPNCS is experimentally evaluated in comparison with a conventional W-NCS over an IEEE 802.11 ad-hoc network. W-MBPNCS outperforms W-NCS in all test cases and its percentage $eRMS$ is shown to remain below 60% under ambient wireless traffic and bursts of packet loss with a mean model packet loss rate of 16% while W-NCS is inoperative under such conditions. Performance of W-MBPNCS is also evaluated when using both IEEE 802.11 MAC and COMAC over a Rayleigh fading channel for different node placement scenarios. W-MBPNCS over COMAC outperforms W-MBPNCS over IEEE 802.11 in all experiments and its controller performance remains virtually insensitive to the distance between the W-MBPNCS nodes up to $85\ m$ as its percentage $eRMS$ always remains below 35% whereas percentage $eRMS$ of W-MBPNCS over IEEE 802.11 exceeds 98% when distance between the controller and sensor/actuator is $85\ m$.

Significant performance gains achieved by the integration of W-MBPNCS and COMAC protocol point out that cooperation is a strong alternative for improving the reliability of industrial wireless networks and the challenges of the wireless control problem can be well addressed with such a multi-disciplinary approach.

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