Wireless Model Based Predictive Networked Control System Over Cooperative Wireless Network

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***Abstract*—Owing to their distributed architecture, networked control systems (NCS) are proven to be feasible in scenarios where a spatially distributed feedback 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 wireless local area networks (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 practical wireless NCS and an implementation of a cooperative medium access control protocol that work jointly to achieve decent control under severe impairments, such as unbounded delay, bursts of packet loss and ambient wireless traffic. The proposed system is evaluated on a dedicated test platform under numerous scenarios and significant performance gains are observed, making cooperative communications a strong candidate for improving the reliability of industrial wireless networks.**

***Index Terms*—Networked control systems, Distributed control, Predictive control, Cooperative systems**

I. Introduction

CONVENTIONAL Networked Control Systems (NCS) where event-triggered controllers and actuators operate in response to time-triggered sensor nodes are suitable for scenarios that require spatial distribution. However, such NCSs require dedicated real-time networks as total end to end latency of the system must be bounded to ensure proper operation. Known shared network technologies such as Ethernet LANs, on the other hand, can not satisfy this constraint due to random medium access latencies and multiple retransmissions caused by unpredictable transmission failures. Consequently, conventional NCSs can not operate reliably over shared networks.

The problem of networked control under unpredictable delays and packet losses have been approached from different directions over the last years. In [1] authors provide a comprehensive survey of the recent work done in this area and an analysis of the significance of network characteristics on the performance of the feedback loop can be found in [2]. In [3] and [4] 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 [5]–[8], 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 the controller or between the controller and the actuator and a transmission failure would adversely affect the performance of the system as given in [1], [2], [9].

As a remedy to these problems, in [10], [11] authors introduce the *Model Based Predictive Networked Control System (MBPNCS)*, establish its stability conditions and present the results of some simulations and experiments. MBPNCS, which assumes a standard NCS architecture with no requirement of direct links and a priori knowledge of the reference signal, utilizes a model of the plant to predict control signals into the future to be able to operate over an IEEE 802.3 Ethernet LAN under variable time delays and packet losses. However, the level of immunity MBPNCS provides against packet losses is only tested with a uniform packet loss model. 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 in some cases dedicated cabling for communication may not be possible. 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 [12]–[16]. 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 this regard, this work considers cooperative communications for enhancing the quality of the wireless links, by reducing the packet losses, the number of retransmissions and ultimately the packet delays.

Cooperative diversity makes use of the neighbors of a node as a set of distributed antennas so that multiple nodes each with a single antenna function as a single multi-antenna system. The wireless broadcast advantage is exploited to disseminate the data to the possible neighbors (cooperators) and via the co-

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operative transmissions, the receiver is provided with multiple copies of the original signal emanating from geographically separated transmitters. This creates spatial diversity at the receiver, resulting in improved link quality [17]–[22]. With its origins in relay channels [23], the topic of cooperative communications has been approached from various perspectives: As [17]–[21] focus on the physical layer cooperative transmission and reception techniques; [22], [24]–[28] mainly concentrate on the access layer techniques along with some emphasis on cross-layer design, to enable cooperation. However, most of these systems require custom designed hardware, which may not be readily available. Furthermore, the existing 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 [16], [29] 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 communication can indeed make a given wireless network more suitable for delay-sensitive applications by decreasing the number of required retransmissions in a fading channel. Recognizing the fact that IEEE 802.11 technology is also becoming popular in industrial environments, enabling cooperation on top of 802.11 is the best and fastest solution for W-NCS. Among the existing cooperative protocols, the Cooperative MAC (COMAC) protocol [27] proposed by one of the authors is a natural and most viable alternative for this purpose, due to its IEEE 802.11 compatibility and low complexity. Approaching the wireless networked control problem from both control and communication perspectives, this paper extends the work presented in [10], [11] to take into account the bursty packet losses of the wireless medium and investigates the possible performance gains that can be achieved through the use of a cooperative wireless communication protocol, COMAC [27]. Specifically, the original contributions of this paper are:

- Implementation of Wireless Model Based Predictive Networked Control System (W-MBPNCS) on a dedicated test platform considering two types of wireless access: IEEE 802.11 and the COMAC protocol.
  - The first part makes use of the IEEE 802.11 protocol implementation available on the test platform, but involves specific modifications on the MAC parameters, which are essential for satisfactory operation of MBPNCS over wireless.
  - The second part involves the faithful implementation of the COMAC protocol on the test platform and emulation of physical layer for cooperative diversity, enabling the operation of MBPNCS over cooperative wireless channel.
- Presentation of detailed experiments and test results for W-MBPNCS over IEEE 802.11 and COMAC, and performance evaluation under typical wireless channel impairments, such as neighboring node interference, block fading and multi-path fading.

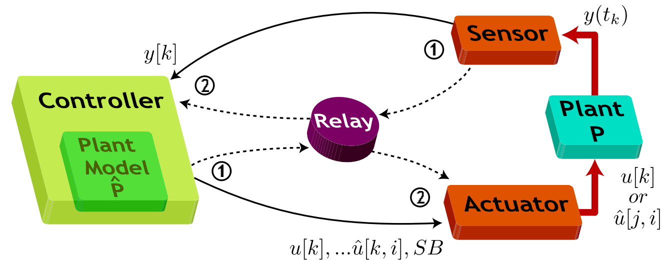

Fig. 1. Overall architecture of W-MBPNCS and cooperation.

W-MBPNCS is a time-triggered wireless networked control system, which is resilient to wireless channel impairments such as unbounded packet latencies and unpredictable bursty 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 the cooperation of neighboring nodes, COMAC achieves higher packet success rates under adverse wireless channel conditions when compared to regular IEEE 802.11 WLANs resulting in superior control performance.

The rest of the paper is organized as follows: Section II provides an overview of the system and some background on wireless access, channel errors, cooperative communications and the control algorithm. Section III presents our W-MBPNCS system, how it handles late and lost packets and introduces W-MBPNCS over COMAC. Section IV presents our test platform, experiments and results. Finally, Section V provides our conclusions.

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 for the current time-step, 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*, the relay cooperates with the source for 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. 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}. This basic access of DCF can be improved by RTS/CTS mechanism to reserve the medium and get rid of the hidden node situations. The same access rules of DCF also apply for the transmission of RTS packets, their collisions and contention resolution.

B. Sources of Wireless Communication Errors

This work considers three sources of wireless communication errors: ambient wireless traffic, block fading and fast (multi-path) fading. Ambient wireless traffic is the wireless traffic generated by neighboring nodes, whereas block fading and fast fading are directly related to the characteristics of the wireless channel. Wireless channel errors occur typically in bursts followed by practically error-free periods rather than occurring completely randomly [30]. Block fading occurs when the duration and separation of these error bursts are longer than the symbol time, 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 symbol time. However, as the characteristics of a wireless channel depend on a multitude of factors, controlling all such contributing factors simultaneously is not possible in a test-bed of limited size and range. Therefore, this work emulates the block fading and fast fading models that are typical in industrial settings [30]–[33]. This way, the performance of the W-MBPNCS can be evaluated in a controlled and reproducible way by varying the wireless channel conditions. In the following, these three sources of errors and the ways in which they are incorporated into the experiments are discussed.

1) Ambient Wireless Traffic: Wireless channel is of broadcast nature, and ambient wireless traffic may interfere with a node's transmissions. Using DCF, the node has to wait for a random amount of time before each retransmission attempt increasing the latency of its packets. Since DCF is stochastic in nature with no upper bound on medium access latency, the node's packets may suffer latencies long enough to cause them to miss their deadlines. In the applicable experiments, a testbed node is utilized to generate disrupting wireless traffic and its effects on the performance of the system are evaluated.

2) Block Fading and Bursty Channel Errors: Block fading causes bursty packet losses and the bursty error characteristics of the wireless channel under block fading can be best modeled by the Gilbert/Elliot channel model [32]. 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 [31] considering channel measurements in an industrial setting.

3) Fast (Rayleigh) Fading: In an industrial setting with numerous obstacles and no direct line of sight between the transmitter and the receiver, multi-path fading causes rapid fluctuations in the received signal strength which result in increased number of retransmissions, increasing packet latency and packet loss. These fluctuations can be modeled with the Rayleigh distribution [30], [33] 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. Cooperative Communications

Multi-path fading causes serious degradation in received signal strength due to the interference between the multipath components of a signal. Since it is less likely for independent signal paths to suffer from deep fades simultaneously, diversity-combining of these independently fading signal paths in order to reduce the fading of the resulting signal is one of the most effective ways to mitigate the effects of multi-path fading [33]. Forming independent multi-hop wireless links reminiscent of multiple input multiple output (MIMO) schemes, cooperative communications employ nodes of a wireless network as a set of distributed antennas. Maximal Ratio Combining (MRC) is to be implemented in the receivers of the cooperating nodes, where signals received at different branches are combined in such a way that output Signal to Noise Ratio (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. This results in improved SNR at the output, hence reduced number of retransmissions, reduced number of packet losses and higher link reliability.

D. The Plant and The Control Algorithm

In order to evaluate the performance of W-MBPNCS, this work considers the position control of a DC motor. The single-input single-output continuous-time dynamics of the plant are given by

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

with the following state, input, output matrices and state vector

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -b/J & K_t/J \\ 0 & -K_v/L & -R/L \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix}$$
$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, x = \begin{bmatrix} \theta \\ \dot{\theta} \\ i \end{bmatrix} \tag{2}$$

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, the continuous-time LTI model of the plant is discretized using zero-order hold assuming that the inputs are piecewise constant over the 10 ms sampling period for a sampling rate of 100 Hz and the following discrete-time dynamics are obtained

$$\begin{aligned} x[k+1] &= \bar{A}x[k] + \bar{B}u[k] \\ y[k] &= Cx[k] \end{aligned} \tag{3}$$

where $\bar{A}$ and $\bar{B}$ are discretized state and input matrices. Next, a full state feedback controller of the form $u[k] = G_r r[k] - Kx[k]$ with a bandwidth of 20.850 Hz is implemented resulting in the following closed-loop dynamics.

$$\begin{aligned} x[k+1] &= (\bar{A} - \bar{B}K)x[k] + \bar{B}G_r r[k] \\ y[k] &= Cx[k] \end{aligned} \tag{4}$$

Finally, in order to estimate the motor speed and current from measured motor position, a no-delay full state Luenberger observer [34] with the following next state and output reconstruction error dynamics is considered.

$$\begin{aligned} \hat{x}[k] &= (I - LC)\bar{A}\hat{x}[k-1] + (I - LC)\bar{B}u[k-1] + Ly[k] \\ \tilde{y}[k] &= (I - CL)C\bar{A}\tilde{x}[k-1] \end{aligned} \tag{5}$$

Since $C = [1\ 0\ 0]$, choosing $L = [1\ L_2\ L_3]'$ yields $\tilde{y}[k] = 0$ meaning that output can be estimated without error. After eliminating one equation this way, a reduced order observer with a bandwidth of 80 Hz is implemented.

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 [35]. 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. Finally, 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. Operating under Ambient Wireless Traffic: W-MBPNCS over IEEE 802.11 with Modified MAC Parameters

Ambient wireless traffic generated by neighboring nodes can cause an NCS's packets to miss their deadlines. As a remedy to this problem, W-MBPNCS over IEEE 802.11 uses a smaller CW_{max} value in order to limit the packet latency variance in case of collisions and smaller $DIFS$ and CW_{min} values for higher medium access priority and lower packet latencies as given in [35]. Modification of the MAC parameters is a natural counter-measure aiming to reduce deadline misses and thus improve controller performance in case of ambient wireless traffic. This approach, specifically covered in [36], is applicable to any delay sensitive wireless application and similar reasonings can be found in [37], [38]. However, as this modification does not improve the wireless link quality, its benefits are limited by the quality of the link in contrast with the case where W-MBPNCS operates over COMAC.

B. Discarding Late Packets: 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 impairments 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 in [35]: The sensor samples, appends a sequence number to and transmits the plant outputs at a period of $T = 1/f_s$ to the controller. The controller operates with a phase shift Φ with respect to the sensor introducing a relative deadline for sensor

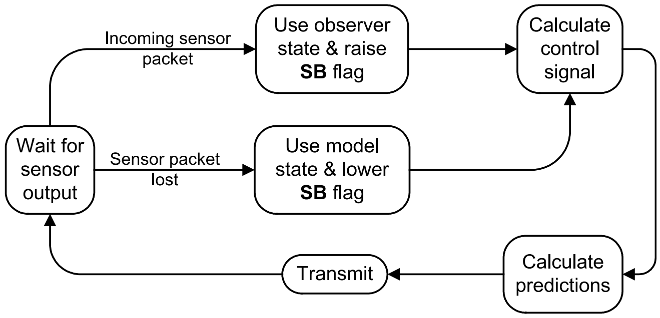

Fig. 2. Operation of the controller node.

packets. In this case, $\Phi = \tau_{network} + T/10$ where $\tau_{network}$ is the typical network delay. However, instead of starting $T/10$ after the first sensor packet, the controller listens for the first n sensor packets ($n = 10$ in this case) and compares the arrival times of the following $n-1$ packets with respect to their expected arrival times derived from the arrival time of the first packet and the sampling time of the system. Since no packet can arrive earlier than expected, the most negative jitter in the arrival times of the following $n-1$ packets is used as an approximation of the additional latency of the first packet. Using this information, the controller can initialize with the correct relative packet deadline even if the first packet suffers an intermittent additional latency. The number of packets to wait for prior to initialization and the relative packet deadline depend on the quality of the wireless link and are determined empirically. Following initialization, each transmitted sensor packet has Φ amount of time before being considered late at the controller. The controller knows the sequence number of the next expected sensor packet at all times and increments this number at each passing deadline regardless of whether the expected packet has arrived or not. Upon receiving a sensor packet, the controller checks the incoming packet's sequence number against the expected sequence number and ignores any packets that fail to meet their deadlines. The initialization and relative packet deadline mechanisms work in the same way between the controller and the actuator.

Per-node relative packet deadlines ensure that a packet either arrives on time or is considered to be lost, effectively reducing unbounded packet latency to packet loss. Since W-MBPNCS nodes operate over a single-hop ad-hoc wireless network, where there exists only one route between a sender and a receiver, it is not possible for packets to arrive out of order; and even if a packet arrives out of order for some reason, it is still dropped due to its missed deadline. One superior alternative to this approach would be to detect and discard late packets at the sender in order to save bandwidth. However, such an approach would require purpose designed hardware capable of tracking the deadlines of queued outgoing packets and aborting those that miss their deadlines.

C. Remaining Stable Under Packet Loss: 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 for the current time step ($u[k]$ or $\hat{u}[k]$ depending on the availability of sensor data), the controller node (Figs. 1, 2) also calculates n future control signal predictions ($\hat{u}[k, 1 \ldots n]$) using state predictions ($\hat{x}[k, 1 \ldots n]$) of the plant model $\hat{P}$ as given in [10], [11].

In W-MBPNCS, the sensor only transmits the measured instantaneous motor position $y[k]$. The observer which estimates the speed and the current from measured plant output and the controller which makes use of the measured and estimated state variables are at the controller node. Since an acknowledgement packet can be lost like any other packet, W-MBPNCS is designed not to require any explicit acknowledgement signals in contrast with the system proposed in [7]. Instead, in case of a communication failure between the sensor and the controller, the controller always assumes that the control signal of the previous time-step has been successfully received by the actuator and has been applied to the plant. Thus, the controller can produce one of two different control signals at a given time-step before continuing with the calculation of future control signal predictions: If sensor data $y[k]$ is available, then the controller uses the state estimate of the observer to calculate the closed-loop control signal $u[k]$. If the sensor packet is lost on its way to the controller, then the controller uses the first state prediction of $\hat{P}$ calculated at the previous time step $\hat{x}[k-1, 1]$ resulting in the control signal prediction $\hat{u}[k]$. In the latter case, the predicted control signal for the current time step $\hat{u}[k]$ and subsequent control signal predictions $\hat{u}[k, 1 \ldots n]$ are valid only if the previous control signal has been applied to P as expected by the controller. Consequently, whenever a controller packet is lost, further controller packets become obsolete until the next time the controller is *synchronized* with the plant by receiving a sensor packet. In order to differentiate such cases, a *sensor based* (*SB*) flag is also stored in the controller packet indicating whether the control signals in a given controller packet are unconditionally valid, i.e. they are based on sensor output $y[k]$, or the control signals in a given controller packet are valid only if the previous controller packet was successfully received by the actuator, i.e. they are based on the state predictions of $\hat{P}$.

In order to cope with this synchronization issue between the actual plant P and the controller, the actuator embodies a state machine (Fig. 3) with two states corresponding to instants when P and the controller are synchronized (*synchronized state*) and out of synchronization (*interrupted state*) as in [10], [11]. When the actuator is in the *synchronized state*, i.e. no controller packets have been lost since the transition to this state, $u[k]$ (or $\hat{u}[k]$) of each packet is applied to P regardless of the condition of the *SB* flag until a controller packet is lost at time-step $j+1$ and the actuator state machine makes a transition to the *interrupted state*. In the *interrupted state*, the actuator ignores the incoming controller packets and applies the predictions of the last controller packet received in the *synchronized state* in a consecutive manner ($\hat{u}[j, 1 \ldots n]$) until a *sensor based* controller packet is received upon which the actuator state machine returns to the *synchronized state*. If

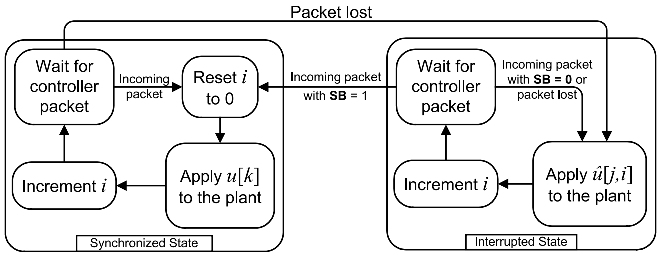

Fig. 3. Operation of the actuator node.

the actuator runs out of predictions in the *interrupted state*, it keeps applying the last control signal prediction $\hat{u}[j,n]$ to P until a *sensor based* controller packet is received. In summary, the model within the controller and the state machine inside the actuator with the associated mechanisms assure that proper control signals are applied to the plant at all times without the need for an explicit acknowledgement mechanism while keeping the prediction correctness within the limits imposed by modeling errors.

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 predictions instead of its own actual states. Thus, at each consecutive packet loss, these control signal predictions deviate from actual closed-loop control signals as $\hat{P}$'s state predictions 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 MBPNCS's stability conditions which is directly applicable to W-MBPNCS can be found in [11] where the stability problem of MBPNCS is treated as a special case of Theorem 2 in [39] assuming full state measurement. Since the stability of W-MBPNCS is guaranteed only under full state measurement, the proposed system may suffer from observer-induced instabilities in various corner cases, even though simulations and experiments show that it is stable under a wide range of operating conditions. Interested reader is referred to [1], [2], [39] for a broader theoretical discussion on the stability of model-based networked control systems in case of communication failures and to [11] for the specific case of MBPNCS. In this work, the number of predictions n is chosen as 50 which is a suitable value for maintaining the stability of the W-MBPNCS platform during the experiments.

D. Mitigating the Effects of Fading: W-MPBNCS over COMAC

W-MBPNCS provides the means to keep a networked control system stable and operational under packet losses; however, the control and reference tracking performance of the system still remains limited by the quality of wireless channel. In this regard, COMAC [27] defines relevant frame formats and frame exchange procedures so that a set of neighboring nodes can communicate cooperatively in order to alleviate the effects of fading. Such cooperative communications result in higher packet success rates, and enhanced controller performance in this case, when compared to non-cooperative IEEE 802.11 due to the diversity gain.

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 the source to the 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, the destination replies with a C-CTS (clear to send) frame. Overhearing the C-RTS and C-CTS frames, the relay sends an ACO (available to cooperate) frame to the source and the two stage cooperative communication commences as given in Fig. 1: In stage-1, the source disseminates the C-DATA-I frame, which is overheard and decoded also by the relay, to the destination. In stage-2 the source and the relay send the C-DATA-II frame, which holds the same payload as C-DATA-I, simultaneously to the destination. After combining and successfully decoding the received data packets, the 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. Use of C-RTS and C-CTS frames along with two-stage cooperative exchange incurs an overhead on the order of several microseconds, however the amount of improvement in the packet success rate overcomes this overhead as studied in detail in [27], [28].

Due to practical reasons of implementation and the limitations of the test-bed, this paper considers only the case where a source always performs cooperation with the same relay. Cooperation and relay selection/actuation in case of multiple relays is another research issue studied on the communication theory side, which is out of the scope of this work. As an example, in [28] the authors introduce an efficient distributed relay actuation mechanism for COMAC that avoids relay racing and provides bounded delay.

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. The Debian GNU/Linux distribution is used as the operating system while the Xenomai real-time development framework is used for real-time support.

Aiming to achieve the most in-depth and faithful implementation possible, this work utilizes modified Linux kernel modules in which the cooperative COMAC protocol is implemented in its entirety and various low-level issues are addressed as follows: Frame filters, Network Allocation Vectors (NAVs) and medium access behaviors of the wireless network interface cards are modified to enable reception of overhead frames and prepare responses. Automatic acknowledgement mechanism is suspended to ensure proper protocol flow and various timeouts, duplicate detection and recovery mechanisms are implemented for robustness. Since the development environment allows changes only on the data link and higher layers, it is not possible to implement physical layer part of cooperative transmission or reception. For this reason, in this work, the COMAC protocol has been implemented at the data link layer and the physical layer operations (i.e., MRC operation) have been emulated. This approach also enabled the emulation of Rayleigh fading, which is very hard to create in a laboratory scenario.

Fig. 4. Network topology of the implementation.

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. The network topology of the implementation is illustrated in Fig. 4.

In the following, the performance of W-MBPNCS over IEEE 802.11 and COMAC is evaluated separately. For W-MBPNCS over IEEE 802.11, the effects of packet loss (block fading) and neighboring node interference are considered and the performance of the system is compared to that of a conventional W-NCS. In experiments with W-MBPNCS over COMAC, the performance of the system is evaluated under various levels of Rayleigh fading for various node distributions and is compared to that of W-MBPNCS over IEEE 802.11.

B. Controller Performance using Modified IEEE 802.11 MAC Parameters

In this section, mainly the performance of 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 Mb/s with quadrature phase-shift keying (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 the system. 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 [31] 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

$$Percentage\ eRMS = \sqrt{\frac{\sum_{k=1}^{n}(\theta[k]-r[k])^2}{\sum_{k=1}^{n} r[k]^2}} \quad (6)$$

where $r[k]$ and $\theta[k]$ are reference and plant positions at time step k. In Figs. 5, 6 percentage $eRMS$ averages of both systems taken over 10 identical runs of 88 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. 7) where a sawtooth reference with a slope of *4 radians/s* is used.

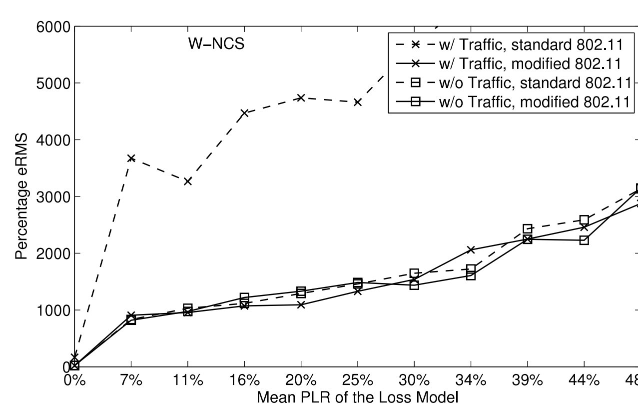

Fig. 5. Controller performance of the conventional W-NCS over IEEE 802.11 under bursts of packet loss, using standard and modified MAC, with and without ambient wireless traffic

In the first test (Fig. 5), 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 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.

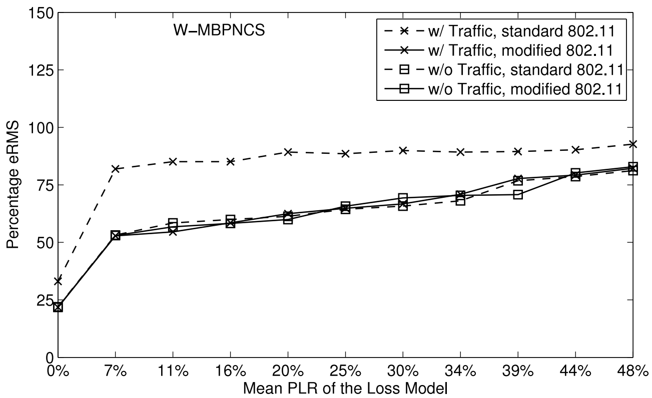

Fig. 6. Controller performance of W-MBPNCS over IEEE 802.11 under bursts of packet loss, using standard and modified MAC, with and without ambient wireless traffic

In the second test (Fig. 6) 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. 7. 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.

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

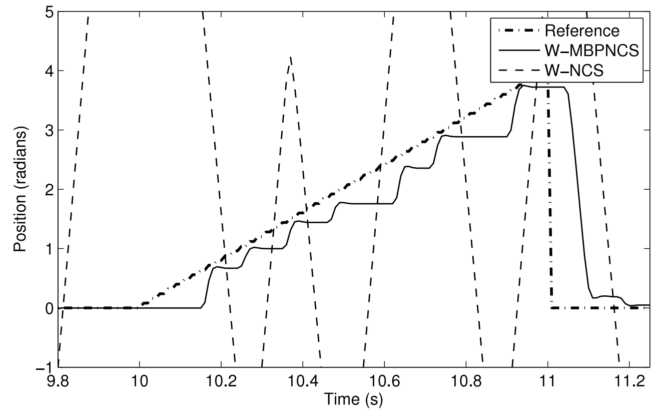

Fig. 7. Sawtooth reference vs. plant output using IEEE 802.11 MAC under bursts of packet loss

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. However, in the following experiments, previously introduced MAC modifications are not applied and the effect of ambient wireless traffic is not considered. Including the results of such trials would be redundant, since it is trivial that those MAC modifications would provide a similar improvement in delays. Moreover, the medium access performance of the direct access mechanism (employed by W-MBPNCS over IEEE 802.11) and the performance of the RTS/CTS mechanism (employed by W-MBPNCS over COMAC) have been shown to be similar in the literature [40]. Therefore, in this section we are mainly concerned with the controller performance under fading and how cooperation (i.e., W-MBPNCS over COMAC) improves the performance assuming standard MAC parameters.

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. 8 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 and never exceeds 6 for other cases. More importantly, when

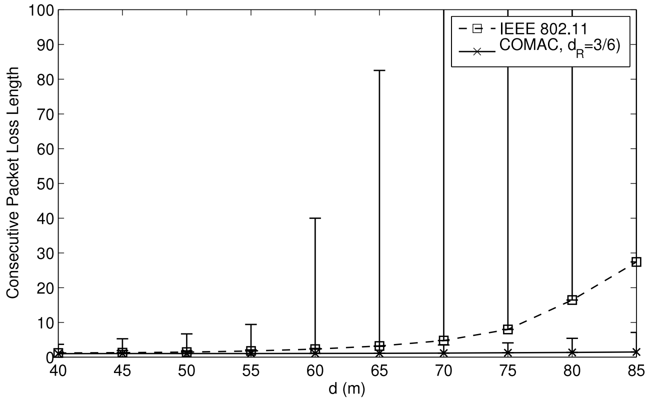

Fig. 8. Mean and maximum lengths of consecutive packet losses at the controller vs. d using both COMAC and IEEE 802.11 MAC

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.

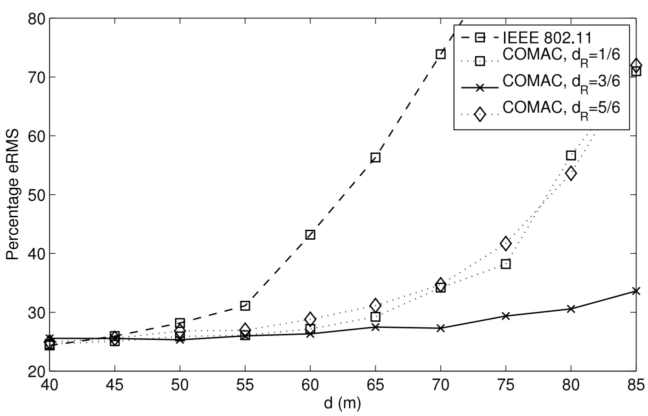

Fig. 9. Controller performance of W-MBPNCS over COMAC under Rayleigh fading vs. d

Fig. 9 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's performance considerably depends on the position of the relay and degrades when the relay is not in the middle. This can be explained as follows: When the relay is closer to the source, chances of initiating a cooperative exchange is higher; but as both the source and the relay are away from the destination, SNRs of C-DATA-I and C-DATA-II at the destination are lower decreasing chances of successful cooperation. When the relay is closer to the destination, chances of initiating a cooperative exchange is lower since SNRs of C-RTS and ACO frames exchanged between the relay and the source are lower. Since W-MBPNCS is a closed loop system whose nodes act both as the source and the destination, both cases cause a degradation in controller performance due to increased packet loss and the best controller performance is achieved when the relay is in the middle as given in Fig. 10.

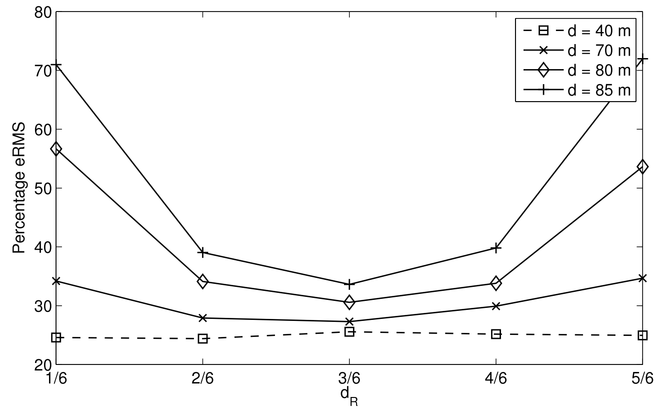

Fig. 10. Controller performance of W-MBPNCS over COMAC under Rayleigh fading vs. d_R

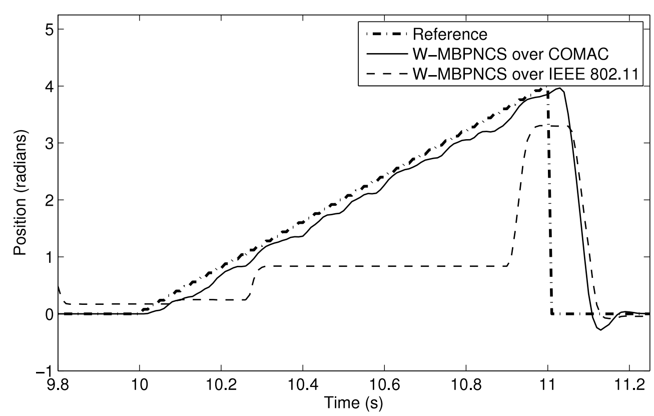

Fig. 11. Sawtooth reference vs. plant output using COMAC under Rayleigh Fading

Finally, Fig. 11 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 the 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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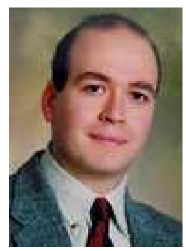

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