Cross-Layer Optimization for Industrial Control Applications Using Wireless Sensor and Actuator Mesh Networks

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***Abstract*—When multiple control processes share a common wireless network, the communication protocol must provide reliable performance in order to yield stability of the overall system. In this paper, the novel cross-layer optimized control (CLOC) protocol is proposed for minimizing the worst-case performance loss of multiple industrial control systems. CLOC is designed for a general wireless sensor and actuator network where both sensor to controller and controller to actuator connections are over a multihop mesh network. The design approach relies on a constrained max-min optimization problem, where the objective is to maximize the minimum resource redundancy of the network and the constraints are the stability of the closed-loop control systems and the schedulability of the communication resources. The optimal operation point of the protocol is automatically set in terms of the sampling rate, scheduling, and routing, and is achieved by solving a linear programming problem, which adapts to system requirements and link conditions. The protocol has been experimentally implemented and evaluated on a testbed with off-the-shelf wireless sensor nodes, and it has been compared with a traditional network design and a fixed-schedule approach. Experimental results show that CLOC indeed ensures control application stability and fulfills communication constraints while maximizing the worst-case redundancy gain of the system performance.**

***Index Terms*—Cross-Layer Optimization, Routing, Scheduling, Wireless Sensor and Actuator Network.**

I. Introduction

GIVEN the benefits offered by wireless sensor and actuator networks (WSANs) compared to wired networks, such as simple deployment and maintenance, low installation cost, lack of cabling, and high mobility, they provide an effective smart infrastructure for factory automation and process control [1]–[3]. Many wireless networking standards have been proposed for industrial processes, e.g., WirelessHART by ABB, Emerson, Siemens and ISA 100.11a by Honeywell [4].

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Some industrial wireless solutions are also commercially available and deployed such as Tropos of ABB and Smart wireless of Emerson. As a standard activity, the internet engineering task force is dedicating efforts on IPv6 routing solutions over the IEEE 802.15.4e standard, which is specifically designed for industrial scenarios [5].

According to TechNavio [6], wireless sensor networking solutions in industrial control applications is one of the major emerging industrial trends. However, the reluctance among industrial end-users to migrate to the latest technology poses challenges to the growth of this market. One of the fundamental reasons of the slow adoption of wireless solutions is that current communication design approaches do not provide deterministic performance to guarantee the stability of the resulting closed-loop systems [7]. The wireless communication inherently introduces non-zero packet error probability caused by the uncertainty of the lossy links and non-zero delay due to the packet transmission and shared wireless medium. Improving the average performance of the network is not enough to guarantee the stability of the control systems. The reliability and the robustness are the essential factors to design an industrial wireless network since the wireless network is susceptible to unpredictable packet losses and faults of the network nodes [8]. Moreover, in the presence of multiple control loops sharing the common imperfect network infrastructure, the reliability and the robustness of each control system need to be guaranteed since an individual control system may affect the stability and safety of the overall system.

Starting from these requirements, an important question to answer is which parameters should be optimized and shared among layers of the protocol stack to guarantee the reliable and robust performance of the overall system. The network redundancy is the critical factor to improve the reliability and the robustness of the systems. Increasing redundancy could significantly improve the network performance, which directly affect the stability of the control systems. In this paper, we consider novel performance metrics to design industrial-WSANs. The stability condition of the control system has been formulated in the form of maximum allowable transfer interval (MATI), defined as the maximum allowed time interval between subsequent state vector reports from the sensor node (resp. controller) to the controller (resp. actuator) [9]. However, such hard real-time guarantees are infeasible to meet for wireless networks since the packet error probability is greater than zero at any point in time. Hence, many

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practical control applications set a stochastic MATI constraint in the form of keeping the time interval between subsequent state vector reports below the MATI value with a predefined probability to guarantee the stability of the control system. Stochastic MATI is an efficient abstraction of the performance of the control systems to design the communication protocol.

The main contribution of the paper is to offer a general framework of WSAN design for process control applications. The framework explicitly targets the need for a more efficient way to develop a general WSAN where nodes attached to plants (resp. controllers) transmit information via a multihop mesh network to a controller (resp. actuator). We propose the cross-layer optimized control (CLOC) protocol based on a co-design between communication and control layers. CLOC relies on a constrained optimization problem, for which the objective is to maximize the worst-case redundancy of the WSAN, and the constraints are the MATI requirements of control systems and the resource schedulability of communication systems. The protocol adapts the operation of the sampling rate of control systems and scheduling and routing of communication systems to optimize the worst possible performance of the control system.

The rest of the paper is organized as follows. In Section II, we summarize existing related works. Section III describes the system model and the assumptions used throughout the paper. In Section IV, we describe the protocol operation in detail. Section V illustrates the scheduling and routing constraints. An optimization problem is posed and solved to optimize the protocol operation in Section VI. In Section VII, we present an adaptive algorithm and implementation of the protocol. Experimental results are presented in Section VIII. Finally, Section IX concludes the paper.

II. Related Works

Communication system design for networked control systems has received little attention in the literature mainly due to the difficulty of formulating the impact of communication on the control performance. Assuming no packet error of a network, some scheduling algorithms optimize the sampling interval and delay parameters of the sensors to minimize the overall performance loss while ensuring network schedulability [10]. The optimization problem is solved using numerical methods due to the high complexity of the control objective and constraints. The formulation however cannot be applied to WSAN where the packet error probability is non-zero at all times. The joint problem of control and communication for building systems is considered in [11]. The authors propose two control schemes, namely the centralized control and the distributed control dependent on the information requirements. Furthermore, a simple transmission scheduling algorithm is proposed to avoid packet collisions for a star topology. The modeling of the interaction between communication and control layers is fairly complex because of the existence of numerous parameters and the non-linear dependencies. Hence, these approaches are hard to be generalized for practical control applications. Moreover, the system scenarios are limited to a simple topology. In contrast to previous works, we consider the most general scenario of wireless mesh networks with multiple source–destination pairs.

Some of the prior works on the communication system design focus on ensuring low end-to-end delay across a mesh network based on a globally synchronized multi-channel time division multiple access (TDMA) medium access control (MAC) [1], [4]. In [12], the authors propose a hybrid access control protocol combining TDMA to guarantee the time deadline of data transmissions and carrier sense multiple access with collision avoidance (CSMA/CA) for network management. The extended version with spatial TDMA is also presented in [13]. In [14], a constrained offline scheduling algorithm is proposed for the IEEE 802.15.4 standard. Given a message deadline, the algorithm optimizes beacon order, superframe order, and guaranteed-time-slot information in a star topology. In [15], gradient-based routing is proposed to enhance energy efficiency while meeting the real-time constraints on top of the IEEE 802.15.4 standard. In [16], three methods, that is segmented slot assignment, fast slot competition, and free node scheduling are proposed to improve the retransmission efficiency for TDMA multihop networks. The proposed algorithms support efficient slot adaptation cased by link or node failures for a given sampling rate and routing path. In [17], a joint optimization problem of rate control, scheduling, and routing is considered for wireless multi-channel networks. The proposed optimization problem is formulated in terms of throughput maximization and fairness problem, as it focuses on the network performance.

Since wireless devices generally rely on either a battery storage or energy harvesting techniques, limiting the energy consumption in the wireless network prolongs the network lifetime for both cases. In [18], the cross-layer protocol jointly considers the routing, random access probability, and power control to maximize the network lifetime. Two optimization problems are formulated by considering the knowledge of the link access probability. Given link access probabilities, the joint optimization problem of power control and routing is shown to be convex and solved by a distributed algorithm. Furthermore, a heuristic algorithm is proposed to solve the general optimization problem including all three layers of power control, link access probability, and routing. In [19], the sensing and routing optimization problem is formulated to maximize overall network utility of the rechargeable devices. By approximating the relationship between sensing and flow rates, a distributed algorithm is used to optimize sensing rate and routing by considering the network topology. However, the reliability and delay requirements are not explicitly considered.

To the best of our knowledge, our paper is the first study formulating simultaneously communication and control performance as a constrained max-min optimization problem to guarantee the reliability of worst-case control system over lossy mesh networks. Even though many joint optimization problems of rate control, scheduling, and routing have been proposed for general wireless networks, a very limited number of the cross-layer optimization algorithms have been implemented through an experimental embedded testbed.

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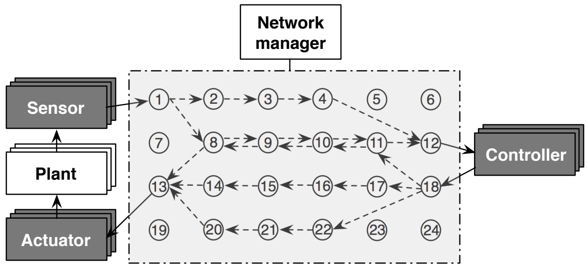

Fig. 1. Overview of the networked control system setup. Multiple plants are controlled by multiple controllers. A wireless network closes the loop from sensor to controller and from controller to actuator. The network includes nodes attached to the plant or controller, and relay nodes.

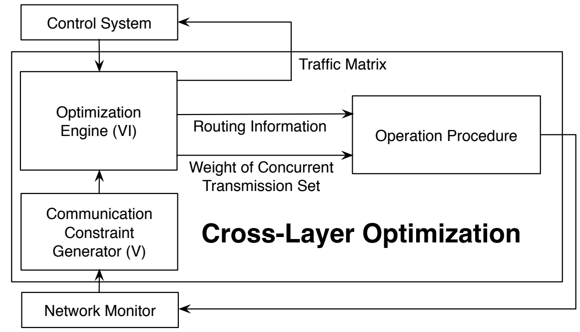

Fig. 2. CLOC system optimization flow. The section numbers in parentheses correspond to the explanation of each component.

III. System Model

We consider the general scenario depicted in Fig. 1, where a plant is remotely controlled over a wireless mesh network [20]. Outputs of plant i are sampled at periodic intervals by the sensors with the time interval of h_i time slots. The packets associated to the state of the plant are transmitted to the controller, over a multihop mesh network. When the controller receives the measurements, it computes the control command. The control commands are then transmitted to the actuator. We assume that the update period of the control signal is equal to the sampling interval. Packets with sampled data (resp. control signal) must reach the controller (resp. actuator) within a MATI requirement. These boundaries are denoted as *control requirements* throughout this paper. The control requirements are chosen by the control designers since they depend on the dynamics of the plants and the choice of control algorithms. The system scenario is quite general, as it applies to any interconnection between a plant and a controller.

This section provides communication and control system models based on the restrictions related to the wireless communication and the stability of the control system.

A. Communication Model

Consider wireless mesh networks where all nodes with unique identifiers communicate through a common transmission channel. For simplicity, we model the network as a directed graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is a set of nodes and $\mathbf{E}$ is a set of directed links connecting nodes in $\mathbf{V}$. We use TDMA as access control protocol since TDMA provides deterministic performance guarantee to the networks with predetermined topology and data generation patterns compared to the random access scheme. Hence, it is widely used for WSANs [4]. Time is slotted and transmissions of packets are synchronized and take exactly one time slot. At any slot, a node is said to be ready if it has a packet ready for transmission at the beginning of the slot (otherwise it is said to be idle). The intended receiver is the node to which the packet is destined.

We use an $N \times N$ traffic matrix to model the amount of traffic demand on each source-sink (s-s) session depending on the sampling interval of the control systems. Note that the sources are sensors (resp. controllers) and the sinks are nodes connected to controllers (resp. actuators) as shown in Fig. 1. The i-th row and j-th column of the traffic matrix λ_{ij} denotes the amount of traffic demand from source i to sink j. If source i transmits a packet to sink j with time interval h_{ij} slots, then the sampling rate is $\lambda_{ij} = 1/h_{ij}$. Recall that the update intervals of both sensor and controller are equal to h_{ij}. Hence, the source i of s-s session (i, j) generates a packet with probability λ_{ij} per slot, and this packet is delivered to the sink j according to the routing policy.

B. Control System Model

The control system designer provides a stochastic MATI constraint to guarantee the stability of the control systems. The stochastic MATI constraint is formulated as

$$\Pr\left[\mu_{ij} \leq \tau_{ij}\right] \geq \Delta_{ij}\ , \quad \forall (i,j) \in \mathbf{H} \tag{1}$$

where μ_{ij} is the state update interval (SUI) defined as the time interval between successful subsequent state vector reports from source i to sink j, $\mathbf{H}$ is the total set of s-s sessions, τ_{ij} is the MATI requirement, and Δ_{ij} is the minimum probability with which MATI should be achieved [9]. The values of τ_{ij} and Δ_{ij} are determined by the control system. Remark that we consider the heterogeneous control system with different τ_{ij} dependent on the plant. The lower MATI requirement is assigned to more critical control systems. Note that μ_{ij} is a function of the communication performance including packet losses and delays. If the time interval between subsequent state vector reports of s-s session (i, j) is less than τ_{ij}, there should be at least one successful transmission within τ_{ij}. Given sampling rate λ_{ij} and MATI τ_{ij}, the number of reception opportunities of the state vector reports is τ_{ij}/h_{ij} where $h_{ij} = 1/\lambda_{ij}$. We assume that the sampling interval is smaller than the MATI constraint, $h_{ij} \leq \tau_{ij}$.

IV. Protocol Operation

The CLOC protocol aims at optimizing the operation of the system. The flow of the system optimization is illustrated in Fig. 2. Its core component is a cross-layer optimizer that bridges the communication system and the control system to guarantee the stability of overall control systems while enforcing the lossy link constraints imposed by the wireless networks. The optimization tool consists of an optimization engine that optimizes the system parameters of communication and control systems, and a communication constraint generator

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that provides a concurrent transmission set and a set of scheduling, routing, and congestion constraints. Note that the concurrent transmission set is the maximal set of feasible simultaneous transmissions of the network to be used for the efficient scheduling.

The inputs of the optimization engine are the MATI requirements of the control systems and the concurrent transmission sets. The engine provides the optimal sampling rate, routing, and weight of each concurrent transmission set to be used. The sampling rate is one of the key parameters since it directly affects the performance of both the communication and control systems. It is also used to update the control systems since it changes the sampling interval of sensors and controllers. The scheduler then assigns the time slots based on the routing and the weight of concurrent transmission sets. The weight of concurrent transmission sets is defined as the fraction of time with respect to the superframe duration in which the links that belong to the concurrent transmission sets are allowed to transmit. This operation is a fundamental component to reduce the complexity of the optimization problem compared to the general routing and scheduling problem, as we will see later. Note that the general routing and scheduling problem based on a conflict graph is NP-hard. The network monitor periodically provides information on the link conditions, which is used to update the concurrent transmission sets of the network. If all link conditions do not significantly change, $\min((1-\upsilon)\mathbf{p}_{t-1}, 0) \leq \mathbf{p}_t \leq \max((1+\upsilon)\mathbf{p}_{t-1}, 1)$ where $\upsilon = 0.01$ and $\mathbf{p}_t$ is the vector of the packet delivery rate (PDR) of the network at superframe t, the optimizer does not update the system parameters.

The network manager relies on global network information since it can achieve excellent performance with a long time-scale stable traffic. The centralized network manager controls the network based on the superframe structure as illustrated in Fig. 3. The time is partitioned into superframes with a fixed length. Each superframe is further divided into operation and data transmission slot. A specific operation message is used to broadcast updates on the optimal decisions. The optimal decisions include the sampling intervals of each sensor and controller, the time slot allocation of scheduling, and the routing paths corresponding to s-s sessions. In general, the optimal sampling interval is much shorter than the duration of the superframe. The data transmission slot uses specific concurrent transmission set which allows multiple simultaneous transmission in the same slot without interference. Hence, the superframe is a combination of different concurrent transmission sets.

Each node starts a packet transmission in its own scheduled slot and waits for an acknowledgement (ACK). If the node fails to receive the ACK within the timeout due to a bad channel, the number of retransmissions variable is increased by one up to the maximum number of retransmissions. When a relay node receives multiple number of data packets from the same s-s session, then it discards the old packet. A node keeps synchronization to its neighbors through a combination of frame-based and acknowledgment-based synchronization, which is similar to the 6TiSCH proposal [5].

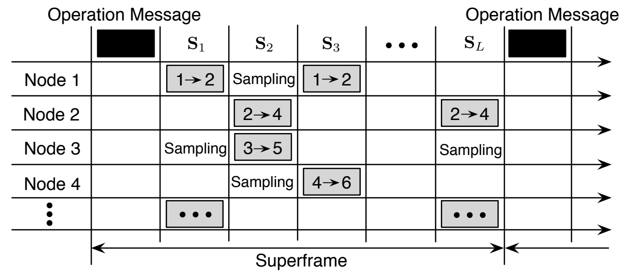

Fig. 3. Superframe structure for a scheduling example.

V. Communication Constraints

Here, we first describe how to compute the concurrent transmission sets for the scheduling without considering any specific network routes. We then present the constraints of the scheduling, routing, and link congestion. The proposed communication constraints efficiently reduce the complexity of the optimization problem.

A. Concurrent Transmission Set Computation

The scheduling of non-interfering links in the same slot is an effective way to optimize the communication resources (see the example in Fig. 3). The only input from the interference model required by our solution is the sets of links that can be scheduled simultaneously. We consider the primary and secondary conflicts of the graph model [21].

The original problem to obtain the optimal concurrent transmission sets is the maximum slot assignment problem based on the conflict graph [21]. In graph theory, an independent vertex set is a subset of vertices such that no two vertices in the subset represent an edge in the graph. A solution of the problem is therefore an independent set containing the largest possible number of vertices. The set of optimal solutions of the maximum slot assignment problem are $\mathbf{S} = \{\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_b\}$ where $\mathbf{s}_m = \{x_m(e_i) : e_i \in \mathbf{E}\}$ and where

$$x_m(e_i) = \begin{cases} 1 & \text{if link } e_i \text{ is allowed to utilized in set } m \\ 0 & \text{otherwise}, \end{cases}$$

$x_m(e_m) = 1$ and $b \leq |\mathbf{E}|$. Note that $|\cdot|$ denotes the cardinality of a set. The maximum slot assignment problem is a hard combinatorial problems, whose solutions require exhaustive search of $|\mathbf{E}|^3$ complexity [21].

We propose a heuristic procedure (see Algorithm 1) to compute the suboptimal concurrent transmission sets. Let the set of reliable links $\mathbf{r} \in \mathbb{B}^{E\times 1}$, where

$$r(e_i) = \begin{cases} 1 & \text{if } p(e_i) \geq p_{\text{rel}} \\ 0 & \text{otherwise}, \end{cases}$$

where $p(e_i)$ is PDR of link e_i and the set of interference links $\mathbf{I} \in \mathbb{B}^{E\times E}$, where

$$i(e_i, e_j) = \begin{cases} 1 & \text{if } e_i \text{ and } e_j \text{ are either primary or} \\ & \text{secondary interference} \\ 0 & \text{otherwise}, \end{cases}$$

are known at the beginning of a slot. Note that we consider the link $p(e_i) \geq p_{\min}$ as the interfering link when we compute the secondary interference where $p_{\min} = 0.01$.

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Input : Set of reliable links, $\mathbf{r} \in \mathbb{B}^{E \times 1}$
Set of interference links, $\mathbf{I} \in \mathbb{B}^{E \times E}$
Output: Total set of concurrent transmissions, $\mathbf{S} \in \mathbb{B}^{E \times E}$

1 **for** $e \leftarrow 1$ **to** E **do**
`// Vector with all elements equal to 0`
2 $\mathbf{v} \leftarrow \mathbf{O}^{E \times 1}$;
`// Set of allowable transmission links`
3 $\mathbf{w} \leftarrow \mathbf{1}^{E \times 1}$;
4 **for** $c \leftarrow 1$ **to** E **do**
`// Permission to transmit`
5 **if** $\mathbf{w}(c) \,\&\, \mathbf{r}(c)$ **then**
6 $\mathbf{v}(c) \leftarrow 1$;
`// Update interference`
7 $\mathbf{w}(\mathbf{I}(:, c)) \leftarrow 0$;
8 **end**
9 **end**
10 $\mathbf{S}(:, e) = \mathbf{v}$;
11 **end**
`// Remove same concurrent transmission sets`
12 $\mathbf{S} \leftarrow$ `Unique` $(\mathbf{S})$;

Algorithm 1: Pseudocode of the algorithm to compute the concurrent transmission sets.

At the first step of the algorithm, a specific link e is assigned to transmit in the time slot (line 1). Without loss of generality, we assume that link i has allocation priority order i. The different priorities among links can be fixed, or varying according to some rule such as round robin or random order. Given the initially activated link e, we initialize the vectors of concurrent transmission set and the set of allowable transmission links (lines 2-3). Steps from line 4 update the allowable simultaneous transmission (line 6) and corresponding primary and secondary interference (line 7). The link is allowed to activate if the link is reliable and does not interfere with already assigned nodes (line 5). If the link is activated, then its corresponding primary and secondary interference are not allowed to transmit (line 7). No additional ready node who has a packet to transmit can transmit successfully without interfering when the algorithm terminates.

B. Scheduling Constraints

As a next step, we derive the constraint on the weight of concurrent transmission sets to assign in the superframe, by considering the schedulability in Fig. 3. We denote α_m as the weight of concurrent transmission set $\mathbf{s}_m$. The sum of the weighted concurrent transmission sets needs to satisfy

$$\sum_{m \in \mathbf{B}} \alpha_m \leq 1 \tag{2}$$

where $\mathbf{B} = \{1, \ldots, b\}$ is the total index set of concurrent transmission sets.

Denote PDR of link e_i of concurrent transmission set $\mathbf{s}_m$ as $p_m(e_i) = p(e_i) x_m(e_i)$, where $p(e_i)$ is PDR of link e_i. Since a link can belong to multiple concurrent transmission sets, the average capacity of link e_i at the MAC layer is $\sum_{m \in \mathbf{B}} \alpha_m p_m(e_i)$. Hence, the traffic load $g(e_i)$ on link e_i requires to meet

$$g(e_i) \leq \sum_{m \in \mathbf{B}} \alpha_m p_m(e_i)\,, \quad \forall e_i \in \mathbf{E}\,. \tag{3}$$

C. Routing Constraints

A routing specifies how traffic of each s-s session is routed across the network. Denote a routing vector $\mathbf{f} = \{f_{ij}(e_l) : e_l \in \mathbf{E}\}$, where $f_{ij}(e_l)$ is defined as the traffic distribution ratio from source i to sink j that is routed on link e_l. Hence, the actual load of the traffic demand on link e_l is $\lambda_{ij} f_{ij}(e_l)$. The amount of traffic flow into relay node k equals the amount of traffic flow out. Hence, the flow conservation constraint at relay node k is

$$\sum_{e_l \in O_k} f_{ij}(e_l) - \sum_{e_l \in I_k} f_{ij}(e_l) = 0\,, \quad i, j \neq k\,, \tag{4}$$

where O_k represents the set of neighbors to which node k is sending traffic and I_k represents the set of neighbors from which node k is receiving traffic.

D. Link Congestion Constraints

The weight of concurrent transmission sets $\boldsymbol{\alpha} = \{\alpha_i : i = 1, \ldots, b\}$ and load distribution of routing $\mathbf{f}$ are feasible if and only if the congestion level of the link is smaller than 1. Given sampling rate, scheduling, and routing, the congestion level is the ratio between the aggregated load and the available capacity among all links

$$\mathrm{Cong}(\boldsymbol{\lambda}, \mathbf{f}, \boldsymbol{\alpha}) = \frac{\sum_{(i,j) \in \mathbf{H}} \lambda_{ij} f_{ij}(e_l)}{\sum_{m \in \mathbf{B}} \alpha_m p_m(e_l)} \leq 1\,, \quad \forall e_l \in \mathbf{E}\,, \tag{5}$$

where $\sum_{(i,j) \in \mathbf{H}} \lambda_{ij} f_{ij}(e_l)$ is the aggregated load demand on link e_l for all s-s sessions and $\sum_{m \in \mathbf{B}} \alpha_m p_m(e_l)$ is the aggregated capacity of concurrent transmission sets for link e_l. If the specific link e_l is congested due to increasing $\lambda_{ij} f_{ij}(e_l)$, then the link congestion constraint forces to reduce the congestion level by increasing the weighed concurrent transmission sets of the scheduling $\sum_{m \in \mathbf{B}} \alpha_m p_m(e_l)$. The sampling rate and the load distribution of routing affect the scheduling policy and vice versa.

VI. Optimization Engine

In this section, we formulate a cross-layer optimization problem of CLOC by considering both communication, including scheduling and routing, and control, including sampling rate based on the MATI requirements. The optimization problem explicitly considers the scheduling and routing constraints derived in the previous section.

A. Objective Function

The objective of our optimization problem is to find a sampling rate, scheduling, and routing to maximize the minimum redundancy of all control sessions. In other words, we optimize the system parameters so that the worst-case optimal performance under the given link condition is achieved. We define the objective function of the problem as the sum of two components, namely, the extra-traffic generation factor and the multipath factor. The extra-traffic generation factor is related to the sampling rate dependent on the MATI requirement. A control system with faster MATI requirements imposes higher sampling rates. We define the extra-traffic generation factor as

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the ratio between the sampling rate λ_{ij} and the inverse of the MATI requirement $\delta_{ij} = 1/\tau_{ij}$,

$$\beta_{ij} = \frac{\lambda_{ij}}{\delta_{ij}}, \quad \forall (i,j) \in \mathbf{H},$$

where $\beta_{ij} \geq 1$ to meet the MATI requirement.

Secondly, we include the possible gain of the multipath routing in the objective function. The multipath uses different relay nodes from the source to the sink. Since the traffic load is dispersed over the network, the maximum node utilization of the network decreases as the number of paths increases. Therefore, the node utilization function is a good performance indicator for the multipath factor. We propose an approximated utilization function of node as the performance indicator of the multipath factor. The utility function of node k is approximated as the sum of the weighted concurrent transmission sets, $\sum_{m\in\Pi(k)} \alpha_m$ where $\Pi(k)$ is the set of concurrent transmission sets using node k as either transmitter or receiver.

Finally, the overall objective function of the optimization problem is the weighted sum of two components, namely, the extra-traffic generation factor and the multipath factor. The optimal sampling rate, scheduling, and routing maximize the minimum redundancy among all sessions of the network

$$(\boldsymbol{\lambda}^*, \mathbf{f}^*, \boldsymbol{\alpha}^*) = \arg\max_{\boldsymbol{\lambda},\mathbf{f},\boldsymbol{\alpha}} \min \left[\epsilon \frac{\lambda_{ij}}{\delta_{ij}} - (1-\epsilon) \sum_{m\in\Pi(k)} \alpha_m \right], \quad \forall (i,j) \in \mathbf{H}, k \in \mathbf{V}, \tag{6}$$

where ϵ is the weighting factor, $0 \leq \epsilon \leq 1$, used to balance two factors of the redundancy. Note that the negative sign of the multipath factor is due to the inverse relation of the node utilization to the multipath factor.

B. Optimization Problem

The CLOC protocol is designed to maximize the minimum redundancy of all control sessions, while meeting redundancy, scheduling, congestion, and routing constraints. The max-min optimization problem is

$$\max_{(\boldsymbol{\lambda},\mathbf{f},\boldsymbol{\alpha})} \quad \epsilon\gamma - (1-\epsilon)\eta \tag{7a}$$

s.t.

$$\text{Redundancy} \begin{cases} \dfrac{\lambda_{ij}}{\delta_{ij}} \geq \gamma, \quad \forall (i,j) \in \mathbf{H}, i \neq j \\ \lambda_{ij} \geq \delta_{ij}, \\ \displaystyle\sum_{m\in\Pi(k)} \alpha_m \leq \eta, \quad \forall k \in \mathbf{V} \end{cases} \tag{7b}$$

$$\text{Schedulability} \begin{cases} \displaystyle\sum_{m\in\mathbf{B}} \alpha_m \leq 1, \end{cases} \tag{7c}$$

$$\text{Congestion} \begin{cases} \dfrac{\sum_{(i,j)\in\mathbf{H}} \lambda_{ij} f_{ij}(e_l)}{\sum_{m\in\mathbf{B}} \alpha_m p_m(e_l)} \leq 1, \quad \forall e_l \in \mathbf{E} \end{cases} \tag{7d}$$

$$\text{Routing} \begin{cases} f_{ij}(e_l) \geq 0, \\ \displaystyle\sum_{e_l\in O_k} f_{ij}(e_l) - \sum_{e_l\in I_k} f_{ij}(e_l) = 0, \forall k \neq i,j \\ \displaystyle\sum_{e_l\in O_i} f_{ij}(e_l) - \sum_{e_l\in I_i} f_{ij}(e_l) = 1, \\ \displaystyle\sum_{e_l\in O_j} f_{ij}(e_l) - \sum_{e_l\in I_j} f_{ij}(e_l) = -1. \end{cases} \tag{7e}$$

The decision variables are the sampling rate of each source $\boldsymbol{\lambda}$, the load distribution of routing $\mathbf{f}$, and the weight of concurrent transmission sets $\boldsymbol{\alpha}$. In Eq. (7a), γ and η of the objective function correspond to the max-min extra-traffic generation factor and the min-max multipath factor, respectively. Eq. (7b) refers the constraint related to the extra-traffic generation factor and the multipath factor. $\lambda_{ij} \geq \delta_{ij}$ refers the minimum sampling rate requirement to guarantee the stability of the control systems. Even though increasing λ_{ij} improves the extra-traffic generation factor of the redundancy, it also increases the congestion level of the link in Eq. (7d). The constraint of Eq. (7b) assigns more network resources as δ_{ij} increases since it increases the traffic demand. Eqs. (7c) and (7d) are the constraints of the schedulability and the congestion level, respectively. The routing constraints of Eq. (4) are listed in Eqs. (7e). By introducing the change of variables $g_{ij}(e_l) = \lambda_{ij} f_{ij}(e_l)$, we transform the optimization problem (7) into the approximated linear programming (LP) problem which can be solved using standard LP solvers. After obtaining the optimal solution, we compute $\mathbf{f}^*$ as $f^*_{ij}(e_l) = g^*_{ij}(e_l)/\lambda^*_{ij}$.

We introduce two other versions of the optimization problem to compare with our proposed solution. First, we consider a traditional network optimization problem to minimize the maximum congestion of the network [22]. The constrained optimization problem is

$$\min_{(\boldsymbol{\lambda},\mathbf{f},\boldsymbol{\alpha})} \quad \rho \tag{8a}$$

$$\text{s.t.} \quad \lambda_{ij} \geq \delta_{ij}, \quad \forall (i,j) \in \mathbf{H}, i \neq j \tag{8b}$$

$$\mathrm{Cong}(e_l) \leq \rho, \quad \forall e_l \in \mathbf{E} \tag{8c}$$

$$\text{Routing constraints}, \tag{8d}$$

where $\mathrm{Cong}(e_l)$ and the routing constraints refer Eq. (5) and the set of Eqs. (7e), respectively. The sampling interval is basically equal to the MATI requirements as from Eq. (8b).

Second, we consider the disjoint approach of the network design, instead of the cross-layer design approach. By fixing the uniformly distributed scheduling policy, the constrained optimization problem is then

$$\max_{(\boldsymbol{\lambda},\mathbf{f})} \quad \gamma \tag{9a}$$

$$\text{s.t.} \quad \frac{\lambda_{ij}}{\delta_{ij}} \geq \gamma, \quad \forall (i,j) \in \mathbf{H}, i \neq j \tag{9b}$$

$$\mathrm{Cong}(e_l) \leq 1, \quad \forall e_l \in \mathbf{E} \tag{9c}$$

$$\text{Routing constraints}, \tag{9d}$$

where $\alpha_m = 1/|\mathbf{B}|$, $\forall m \in \mathbf{B}$.

VII. Protocol Implementation

In the previous sections, we showed how to determine the optimal sampling rate, schedule, and routing by solving an optimization problem. Here, we present the practical implementation of the proposed protocol including the link monitoring procedure and the critical operation mode.

A. Link Monitoring Procedure

At the beginning of the superframe, the network manager periodically calculates the optimal parameters based on the wireless link condition. To estimate the global link condition, each link quality is estimated at a local node and sent to the

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network manager. The lower transmit power level is used by all nodes to forward the information of the link condition over multihop paths. We propose the following strategy. Each node computes PDR by using received data packets. Even if it is not a desired receiver, the data packet is still useful to monitor the link connectivity with neighbors. The PDR information is then encoded in the ACK message and sent to the transmitter.

B. Critical Operation Mode

Our routing path selection criterion combines long-term quasi-static scheduling and routing with the short-term alternative link selection. We use a quasi-static routing, so that the fractions of traffic on the paths between all s-s sessions do not change over a long time period. Hence, it can achieve excellent performance with a long time-scale stable condition. However, most wireless links are highly unstable and correlated over time and space [23]. Therefore, each node runs a short-term adaptive algorithm of the multipath routing and the buffer management dependent on the SUI performance of the session. The sink continuously monitors the SUI performance of each session. If the SUI is greater than $\omega\tau$, $\mu \geq \omega\tau$ where $\omega = 0.8$, then the sink marks the corresponding session as a critical session. The information about the critical session is piggybacked on ACK messages and does not require additional message passing. If a node receives the ACK message with the list of the critical sessions, it retrieves the critical session IDs and goes to the critical operation mode for those sessions. Note that all relay nodes share the list of the critical session from the source to the sink. When a node is in the critical operation mode, it starts a critical timer whose duration is $\theta\tau$ where $\theta = 2$ for its critical sessions. When the critical timer expires, the node goes back to normal operation mode.

During the critical operation mode, each node supports distributed routing decisions when forwarding a packet. When a node receives a packet from the critical session, the node forwards the corresponding packets to all possible intended receivers of the next hop for the critical session. In addition, the node gives the highest priority for a set of packets corresponding to the critical session to reduce the waiting time in the buffer. If a node successfully transmits a data packet to all possible intended receivers, the critical timer of its critical session is discarded and goes to normal operation mode. This simple mechanism improves the end-to-end reliability of the critical paths. The traffic load of the local areas might increase due to its transmission policy. However, the scheduler prevents the performance degradation because each node has dedicated transmission slots.

VIII. Performance Evaluation

In this section we provide an extensive set of experiments to validate the CLOC protocol. We implement the protocol and analyze the performance in terms of both communication and control aspects. The proposed TDMA-based protocol is implemented on top of the IEEE 802.15.4 physical layer. The experimental testbed is comprised of 24 TelosB nodes and a root server, mounted uniformly in the ceiling of the laboratory, to mimic a topology as shown in Fig. 1. The network

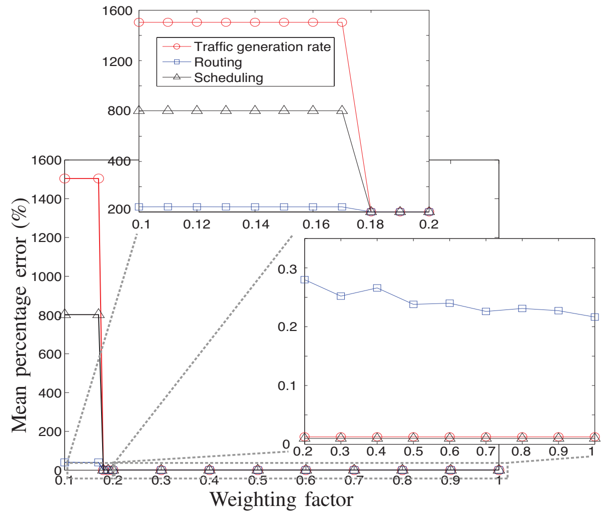

Fig. 4. Mean percentage error of the CLOC solution with respect to the optimal solution as a function of different weighting factors $\epsilon = 0.1, \dots, 1$.

manager is a software on the root server. The laboratory has a typical indoor environment with concrete walls with the space of dimension 15m×25m. All nodes in the experiments run TinyOS and use the CC2420 802.15.4 chip with fixed transmit power -7dBm on channel 26. Each sensor node is located 5m from each others to ensure two or three neighbors in the communication range of each node, as recommended by WirelessHART's best practice [4]. Global clocks of the network nodes across the entire network are synchronized using the flooding time synchronization protocol.

A node acting as a source generates packets periodically with sampling rates (λ pkt/slot) and forwards packets to a sink. The network manger sends the optimal solution, namely the sampling rate, the load distribution of routing, and the weight of concurrent transmission sets to all nodes using the maximum transmit power 0dBm. We define the slot time and the length of the superframe equal to 10ms and 800ms, respectively. To evaluate the performance, we run CLOC with different requirements of 3 experimental runs of 2 hours each.

We compare the proposed CLOC protocol, against alternative optimization approaches, here referred to as *Min-Con* [22] and *Fix-S* solutions. The traffic load, scheduling, and routing of CLOC are obtained by solving the optimization problem (7). Similarly, the solutions of Min-Con and Fix-S are obtained by solving the optimization problems (8) and (9), respectively. Min-Con is focused on a performance metric to minimize the maximum congestion among all links, which represents a traditional network design approach [22]. In addition, Fix-S represents the layered design approach, without considering the cross-layer interactions.

We first compare the optimal solution of the mixed-integer LP problem (7) and the CLOC solution of the approximated LP problem. We obtain the optimal solution by using CPLEX. Fig. 4 shows the mean percentage error of the CLOC solution with respect to the optimal solution as a function of different weighting factors $\epsilon = 0.1, \dots, 1$. The CLOC solution of the LP problem matches quite well the optimal solution. The mean

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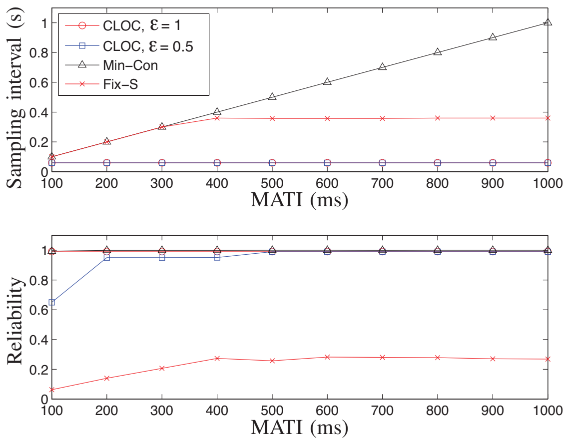

Fig. 5. Sampling interval and end-to-end reliability for CLOC with $\epsilon = 1$, CLOC with $\epsilon = 0.5$, Min-Con, and Fix-S with the number of sessions $M = 4$ as a function of different MATI requirements $\tau = 0.1, \ldots, 1$s.

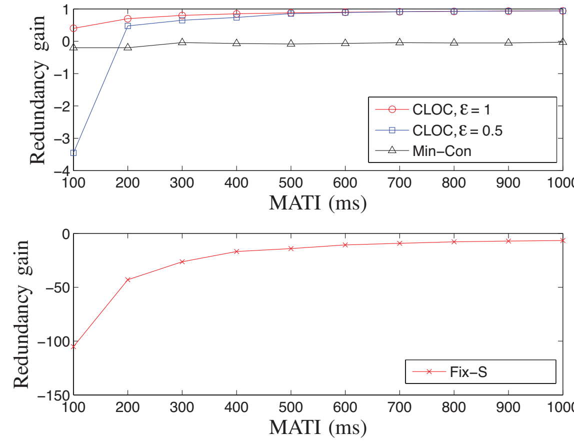

Fig. 6. Redundancy gain for CLOC with $\epsilon = 1$, CLOC with $\epsilon = 0.5$, Min-Con, and Fix-S with the number of sessions $M = 4$ as a function of different MATI requirements $\tau = 0.1, \ldots, 1$s.

percentage error of the CLOC solution is under 0.3% for $\epsilon \geq 0.18$. However, the error significantly increases when $\epsilon < 0.18$ because the integer constraints related to the weight of concurrent transmission sets $\boldsymbol{\alpha}$ become more strict as the weighting factor ϵ decreases. Remind that the weighting factor ϵ affects the tradeoff between the extra-traffic generation factor and the multipath factor of the redundancy in the optimization problem. As ϵ decreases, the network manager assigns more objective weight to achieve the multipath factor rather than the extra-traffic generation factor. Therefore, the objective function forces to spread the weight of concurrent transmission sets when the weighting factor decreases. This is not a limitation since the CLOC protocol gives good performance for larger weighting factor, as we will see later.

A. Communication Performance

Fig. 5 shows the sampling interval and end-to-end reliability for CLOC with $\epsilon = 1$, CLOC with $\epsilon = 0.5$, Min-Con, and Fix-S as a function of MATI requirements $\tau = 0.1, \ldots, 1$s with the number of sessions $M = 4$ and $\Delta = 0.95$. These MATI requirements are chosen as representative for industrial control applications. As the MATI requirement is smaller, the control system requires a faster sampling rate. Each packet is required to reach the sink within τ with a probability of $\Delta = 0.95$. Note that the average number of hops of CLOC from sources to sinks is around 2.25 for this set of experiments. The sampling interval of Fix-S converges to around 0.357s with low end-to-end reliability due to the uniformly distributed schedule. While the sampling interval of Min-Con is equal to the MATI, it is interesting to observe that the optimal sampling interval of CLOC is approximately constant around 60ms independently of the MATI requirements. The end-to-end reliability of Min-Con is slightly greater than the one of CLOC with $\epsilon = 1$. The main reason is that as the sampling interval increases, each node has more time slots to transmit or receive a data packet. In other words, Min-Con has more opportunities to retransmit a data packet if it is needed due to its longer sampling interval. While using a longer sampling interval increases the end-to-end reliability, it decreases the sampling rate and the update rate of control signal for control systems. Hence, SUI is a function of the end-to-end reliability and the sampling interval. There is an optimal value for the sampling interval beyond which nodes waste the allocated time slots without carrying new information. CLOC optimizes the SUI performance based on a tradeoff between the reliability and the sampling interval.

To characterize the performance of the communication system, we define the redundancy gain as $\Gamma = \frac{\tau - \mu_{95}}{\tau}$ where τ is the MATI requirement and μ_{95} is the 95th percentile of measured end-to-end SUI of all s-s sessions. Remind that SUI is one of the most critical factor to guarantee the stability of the control systems. Hence, a percentile is used to show the level of confidence. Obviously, the closer Γ is to 1, the better the system performance. If $\Gamma < 0$, it means that the MATI requirement of the control systems is not met.

Fig. 6 compares the redundancy gain for CLOC with $\epsilon = 1$, CLOC with $\epsilon = 0.5$, Min-Con, and Fix-S as a function of MATI requirements $\tau = 0.1, \ldots, 1$s with the number of sessions $M = 4$ and $\Delta = 0.95$. In general, the redundancy gain increases as the MATI increases, i.e., a slower control system. Although there is a strong dependence of the redundancy gain on MATI requirement, our proposed CLOC with $\epsilon = 1$ is more reliable than the alternative Min-Con and Fix-S. The redundancy gain for CLOC approaches 1 for $\tau > 0.7$s. Therefore, the experimental results show clearly the effectiveness of our adaptive CLOC protocol to guarantee the MATI requirement.

Both Min-Con and Fix-S do not ensure MATI satisfaction, i.e., it can happen that $\Gamma \leq 0$. Remind that the sampling rate of Min-Con is equal to the minimum traffic demand of the MATI requirement. Even if the reliability of the network is very high by minimizing the maximum congestion level of the network, the wireless link have bursty losses in the short time-scale [23]. As a result, Min-Con does not support reliable operations under worst conditions. Moreover, the redundancy gain of Fix-S is significantly worse than other solutions due to the uniformly distributed schedule, which is independent of MATI requirement, sampling rate, and routing. The major portion of the assigned time slot may not be used due to the

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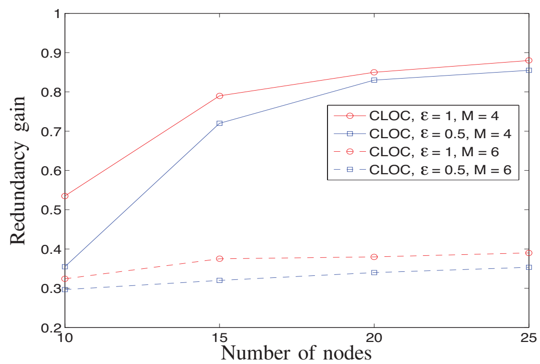

Fig. 7. Redundancy gain for CLOC with $\epsilon = 1$ and $\epsilon = 0.5$ with the number of nodes $N = 10, \ldots, 25$ as a function of different number of sessions $M = 4, 6$ and the MATI requirements $\tau = 0.5$s.

inefficient schedule overhead. On the contrary, the proposed CLOC protocol guarantees good performance and efficient use of network resources.

Now, we analyze the effect of the number of nodes on the network performance. Fig. 7 shows the redundancy gain of CLOC with $\epsilon = 1$ and $\epsilon = 0.5$ as a function of the number of nodes $N = 10, \ldots, 25$ with the number of sessions $M = 4, 6$ and the MATI requirement $\tau = 0.5$s. In general, the redundancy gain decreases as the number of nodes decreases due to a smaller number of available routing paths. By decreasing $\epsilon \leq 1$, CLOC introduces more routing paths in order to increase the multipath factor of the optimization problem. Note that the diversity of the routing paths increases as the number of relay nodes increases. Hence, the effect of the number of nodes is more critical for CLOC with lower weighting factor $\epsilon = 0.5$ than the one with $\epsilon = 1$. Moreover, the redundancy gain of CLOC with $\epsilon = 0.5$ is worse than the one with $\epsilon = 1$ when the number of sessions increases due to the inefficient multipath.

B. Control Performance

In this subsection, we illustrate the effect of the network performance on the stability of the control system. We consider a linear time invariant system, where each sensor and controller transmits measurements or control messages over the network. The plant is given by a double integrator system, which is a typical example in control, such as an industrial robotic arm. The corresponding state-space model is

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 & 1/T \\ 0 & 0 \end{bmatrix} \mathbf{x}(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \mathbf{u}(t) \qquad (10)$$
$$\mathbf{y}(\mathbf{t}) = \begin{bmatrix} 1 & 0 \end{bmatrix} \mathbf{x}(t)$$

where $T > 0$ is the time constant of the plant. The controller is a state feedback $\mathbf{u}(t) = -[4 \;\; 2]\, \mathbf{x}(t)$. When T is close to 0, the control system requires a faster sampling rate, i.e., the control system is faster. Hence, the MATI requirement τ becomes smaller as T is smaller. The experimental results of the network performance are taken as an input to the simulation environment that models the plant and the controller.

In Fig. 8, we compare the step response of the system by plotting the output signal (a) and control signal (b) for an ideal case, CLOC with $\epsilon = 1$, Min-Con, and Fix-S for the illustrated closed-loop control system with the number of sessions $M = 4$, MATI requirement $\tau = 0.2$s, maximum amplitude of the control signal $u_{\max} = 10$, and time constant of the system $T = 6$. Each session corresponds to the wireless connection from the sensor to the controller or from the controller to the actuator, as shown in Fig. 1. Note that for the ideal case, the communication is perfect so there is no packet loss and delay. Observe that the step response for CLOC with $\epsilon = 1$ follows well the one in the ideal case. Even though the Min-Con protocol stabilizes the control system, it increases the rise time and the settling time significantly due to the poor SUI performance. Moreover, the control signal is highly oscillating and saturates for longer time. The closed-loop system is unstable for the Fix-S case due to the high mean and variance of SUI. In fact, it is known that a heavy tail of the SUI distribution significantly degrades the stability of the closed-loop system.

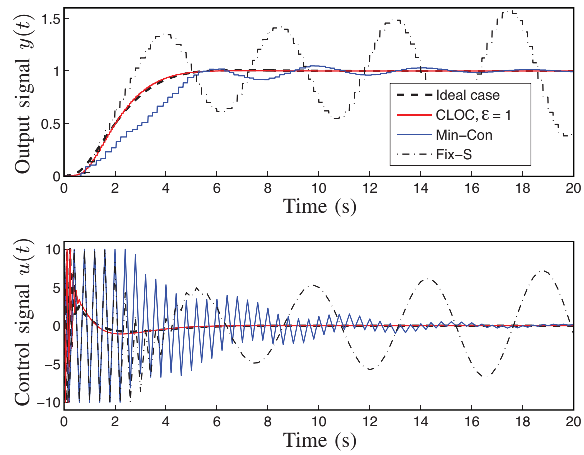

Fig. 8. Effect of the network performance for ideal case, CLOC with $\epsilon = 1$, Min-Con, and Fix-S on a state feedback control system with the number of sessions $M = 4$, the MATI requirement $\tau = 0.2$s, the maximum amplitude of the control signal $u_{\max} = 10$, and the time constant of the control system $T = 6$.

IX. Conclusions and Future Work

In this paper, we proposed the CLOC protocol to jointly optimize communication and control systems. The design approach relies on a constrained max-min optimization problem, where the objective function is the redundancy combining the extra-traffic generation factor and the multipath factor, and the constraints are stability and resource schedulability. The decision variables of the optimization problem are the scheduling and routing of the communication layer, and the sampling rate of the control system. The optimal operation point of CLOC is achieved by solving an LP optimization problem, which adapts to control system requirements and wireless link conditions. We provided a testbed implementation of the protocol, building a network with wireless sensors and actuators, and compared with a traditional network design and a fixed-schedule approach. Experimental results demonstrated that the CLOC protocol ensures stability and schedulability constraints while maximizing the worst-case redundancy of

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the network. Furthermore, the results indicated that CLOC performs significantly better in terms of redundancy gain compared to other approaches. It was also shown that the solution guarantees suitable control performance.

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