Delay-Reliability Model of Industrial WSN for Networked Control Systems

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***Abstract*—In a so-called ‘Smart Factory’, sensors, actuators, and a processing logic are interconnected via wireless communication. A popular class of industrial processes is Networked Control Systems (NCS), where the sensor, controller, and actuator of a control system are distributed over a network. Wireless brings several benefits to NCS but affects their performance. This aspect is particularly critical, as NCS pose stringent delay and reliability requirements to data packets in order to fulfil a desired Quality of Control (QoC). Industrial Wireless Sensor Networks (IWSN) is a candidate communication technology to haul NCS traffic. IWSN, however, suffer from packet loss caused by the harsh industrial environment. The characterization of the impact of delay and packet loss on the QoC of NCS is a challenging task, as it requires the analysis of mutually dependent random processes. We tackle this investigation deriving a delay-reliability model for IWSN based on the Loop Success Probability, a metric that associates the network performance to the QoC of the NCS. Initially, the effect of Loop Success Probability on QoC is evaluated, then, it is mathematically related to the end-to-end delays of IWSN packets. The model provides a connection between IWSN parameters and QoC and is used to define their operating regions. Via measurements of an IWSN testbed and a simulated NCS, we prove the validity of the proposed model.**

***Index Terms*—IWSN, NCS, QoC, Delay, Reliability, Testbed.**

I. INTRODUCTION

The Fourth Industrial Revolution will redefine current factories by connecting machines and processes in a so-called ‘Smart Factory’. Networks of sensing, processing and actuating elements will be interconnected via wireless communication. Thanks to flexible ad-hoc deployments and low energy consumption, Industrial Wireless Sensor Networks (IWSN) are a candidate communication technology to haul industrial traffic.

A significant portion of industrial traffic arises from Networked Control Systems (NCS), where distributed sensors and actuators are interconnected with the control logic of an automatic control system. As represented in the NCS architecture of Fig. 1, every sampling interval, a sensor reading is sent to the controller that computes a control command for the actuator to steer the physical plant [1]. The deployment of an NCS over a wireless network improves ease of installation, maintenance, and flexibility [1], at the price of coupling the NCS performance with the communication network. NCS pose stringent delay and reliability requirements for data communication. Failure in delivering actuation commands introduces a penalty in the Quality of Control (QoC) of the NCS and can cause instability [1].

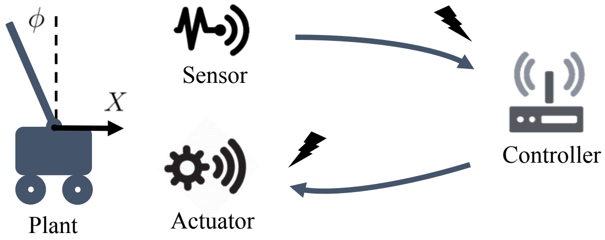

Fig. 1: Architecture of a Networked Control System constituted by a two-hops Industrial WSN affected by packet loss.

Timely and reliable packet delivery is particularly challenging in IWSN due to random packet loss arising from the harsh industrial environment, which is characterized by strong signal fading caused by moving machines and interference from coexisting wireless technologies [2]. To combat packet loss, a popular approach is to schedule re-transmissions at the price of increased, non-deterministic delays. Although existing scheduling strategies provide a desired reliability within a delay bound [3]–[5], none of them investigates their implications for an NCS served by an IWSN as represented in Fig. 1.

The precise characterization of delay and reliability in an NCS constituted by a two-hops IWSN is challenging, as it requires the analysis of multiple mutually dependent random processes and their impact on the NCS. In this paper, we tackle this problem proposing a delay-reliability model based on the *Loop Success Probability* (P_{LS}), a metric that relates the delay and reliability of the IWSN to the QoC of the NCS. First, the effect of P_{LS} on QoC is evaluated via simulations. Then, the analytical model of P_{LS} is derived in terms of end-to-end delay and reliability of an IWSN employing the TSCH medium access. The model provides a connection between IWSN parameters and QoC and is used to define their operating regions. Via measurements of an IWSN testbed and an emulated NCS, we prove the validity of the proposed delay-reliability model and its relationship to QoC.

The rest of the paper is structured as follows. Sec. I-A discusses the related work. Sec. II introduces the concept of P_{LS} and evaluates its relationship to QoC, while Sec. III presents its analytical model for IWSN. Sec. IV describes the IWSN testbed implementation and the validation results of the model. Sec. V concludes the paper.

A. *Related Work*

The investigation of network delays and packet loss in IWSN for industrial applications has received considerable attention in the literature [1]. We cluster the available works into *control-related* and *network-related* approaches.

A large number of control-related research studied network delays and packet loss in NCS. Authors in [6]–[9] included these effects in the design of the control system and evaluated its performance. Their analysis, however, did not include a realistic model of the IWSN medium access and propagation environment. Similarly, authors in [10], [11] evaluated the impact of delay and packet loss on NCS, however, no realistic network is considered. A different approach is studied by authors in [12]–[14], which analyzed packet loss and delay for a TDMA medium access. Pesonen et al. [12] investigated the operation of an NCS for different TDMA schedules with frequency hopping, and developed a Markov Chain to model the reliability in the network. Their approach, however, does not provide analytical insights in the delay and reliability achieved by the network, but only observes them via simulation. Park et al. [13] characterized the delay-reliability performance of an IWSN subject to loss and delay, however, only for contention-based medium access. In their recent work [14], they derived optimal schedules for contention-based and contention-free medium access schemes, but no analytical model of the delay and reliability was given.

On the other hand, most of the network-related approaches focus on the definition of schedules to fulfil delay and reliability requirements in a multi-hop network and hardly consider the interaction with a real NCS. Authors in [15], [16] investigated re-transmission strategies for IWSN to compensate packet drops. The methods are evaluated in terms of delay and reliability, but no analytical model was derived. Furthermore, several scheduling schemes were proposed [3]–[5], [17], [18]. Liu et al. [17] constructed schedules for control loops and Saifullah et al. [18] formulated an optimization problem to find schedules respecting a desired delay-bound. However, in both cases, packet loss is not taken into account. Authors in [3] and in [4], [5] formulated scheduling problems to achieve maximum reliability within a delay bound and minimum latency within a desired reliability bound. All these methods, however, do not characterize the exact distribution of delays and reliability in the network. Finally, authors in [19], [20] tackled the investigation of end-to-end delay bounds for IWSN communication subject to packet loss. Munir et al. [19] characterized the network delays observing the burstiness of packet drops, while Saifullah [20] modelling the channel contention and transmission conflicts of different flows in the network. However, both cases did not characterize the end-to-end delay distribution of the packets, and their scenario only considered the uplink transmissions of sensor packets to a central sink, which is not applicable to a two-hops NCS.

With the current state of the art, a major challenge still exists in modelling the delay and reliability of IWSN to achieve a specific QoC of the NCS. Through this paper, we aim to bridge this gap introducing a delay-reliability model for NCS operating over a two-tops TSCH IWSN. The model is based on *Loop Success Probability*, a metric that relates the QoC of the NCS to the network performance, and enables the analysis of TSCH schedules for a desired QoC.

II. NCS QOC CHARACTERISATION

The architecture of an NCS, depicted in Fig. 1, comprises a Sensor, a Controller, and an Actuator. In each control loop, a measurement is taken by the Sensor and sent to the Controller, which in-turn computes the actuation command and sends it to the Actuator to steer the physical system. In this way, the trajectory of the physical system is remotely controlled over the network. When packets are correctly delivered, the physical system is flawlessly controlled. However, if packets are delayed or lost, the control loop is interrupted and the physical system deviates from the desired trajectory, potentially becoming unstable. To quantify this effect, different Quality of Control (QoC) metrics can be defined. In this section, we evaluate the impact of random network delays and packet loss on the NCS' performance via the *Loop Success Probability* (P_{LS}), i.e. the probability that NCS messages are correctly delivered at each control loop. Via extensive simulations of an Inverted Pendulum, we study the impact of P_{LS} on different QoC metrics.

A. *Inverted Pendulum - A classical NCS*

The Inverted Pendulum has a long tradition in literature and industry. The goal of the remote controller is to vertically suspend the pendulum with appropriate movements of the cart. The evolution of an LTI Inverted Pendulum can be represented by the following stochastic discrete-time model for time instants k and $k+1$

$$X(k+1) = AX(k) + BU(k) + W, \quad (1)$$

$$U(k) = -KX(k), \quad (2)$$

where $X(k) = \left[x_k, \dot{x}_k, \phi_k, \dot{\phi}_k\right]$ is the state vector of the system measured by the Sensor and $U(k)$ is the actuation command generated by the Controller to steer the plant. The state variables x and ϕ represent, respectively, the cart's position and the vertical angle of the pendulum as shown in Fig. 1. We assume that the pendulum's dynamics are affected by white Gaussian noise W with zero mean and covariance R, introduced by the linearization error and modelling limitations of the real system. The system matrices A and B are obtained by linearizing and discretizing the dynamical model of the pendulum as shown in [21], and the control gain K is obtained solving the algebraic Riccati equation according to the Linear Quadratic Regulator (LQR) control algorithm.

B. *Quality of Control and Loop Success Probability*

In order to achieve a desired trajectory of the dynamical system, actuation commands have to be applied every sampling period T_S. Thus, data must be delivered to both Controller and Actuator within T_S. Due to random packet drops and delays, it can happen that the actuation command does not reach the

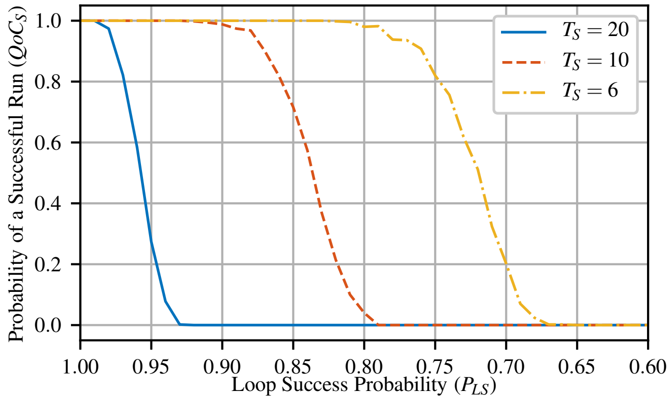

Fig. 2: Impact of Loop Success Probability on the NCS stability (QoC_S) for different sampling periods T_S.

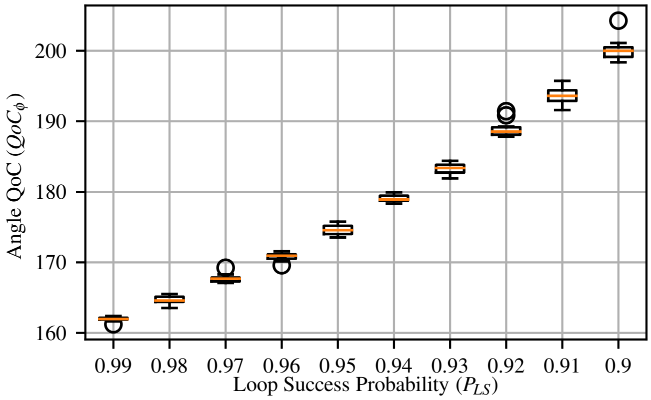

Fig. 3: Impact of Loop Success Probability on the NCS performance (QoC_ϕ) for $T_S = 10$.

plant on time. We model this condition using the *Loop Success Probability* (P_{LS}), that is defined as the probability that the end-to-end (E2E) delay of a control packet, generated at the sensor and received at the actuator after processing at the controller, is smaller than T_S

$$P_{LS} \triangleq \mathrm{P}[D_{E2E} < T_S]. \tag{3}$$

The definition of P_{LS} incorporates the delay and reliability of the network and the requirements of the control loop.

When the actuation message is not received, the actuator assumes a default value, in our case $U = 0$, causing a divergence between the system's dynamic and the controlled trajectory. This causes large deviations of the vertical angle from the desired control reference $\phi_{ref} = 0$, which lead to a reduced performance of the NCS and, in the worst case, to instability. To quantify these effects, we introduce two QoC metrics and evaluate them via simulations of the Inverted Pendulum for different P_{LS}. The *Angle QoC* measures the performance of the NCS and is calculated integrating the absolute deviation of ϕ_k from ϕ_{ref} for an experiment duration of T_E sampling periods

$$QoC_\phi = \sum_{k=1}^{T_E} \mid \phi_k - \phi_{ref} \mid . \tag{4}$$

The *Stability QoC* is defined as the probability that the pendulum is stable for the entire experiment duration. We consider that the pendulum is stable if the trajectory of the vertical angle is bounded by a maximum angle ϕ_T, i.e. $|\phi_k| < \phi_T \ \forall k$. The value of ϕ_T depends on the combination of the physical characteristics of the Inverted Pendulum, such as the precision of sensor and actuators, and the employed control logic. By performing multiple runs of the Inverted Pendulums, the Stability QoC can be calculated as

$$QoC_S = \mathrm{P}[\mid \phi_k \mid < \phi_T] = \frac{\text{N. of stable runs}}{\text{N. of runs}}. \tag{5}$$

We evaluate QoC_ϕ and QoC_S with extensive simulations of the Inverted Pendulum for different values of P_{LS} and T_S. Each sampling period, actuation messages are received with probability P_{LS} and lost with probability $1 - P_{LS}$. The system matrices A and B are obtained discretizing the continuous-time model of the pendulum [21] and are used to calculate the LQR control gain K for each sampling period T_S. R is a diagonal matrix with values $\sigma^2 = 10^{-3}$ on the diagonal. The maximum angle ϕ_T is set to 30°. Fig. 2 shows the impact of P_{LS} on QoC_S for systems with different T_S. Each curve is obtained repeating 10^2 simulations of $T_E = 10^5$ sampling periods. The results show that P_{LS} has a strong impact on the stability of the system, that is, the stability reduces when the P_{LS} decreases. All systems experience a transitional region for stability for different intervals of P_{LS}. Systems with shorter sampling periods tolerate lower P_{LS} as they can control the dynamics of the system more often.

The impact of P_{LS} on the Angle QoC is evaluated only for P_{LS} that achieve stability for the entire experiment duration. Therefore, in Fig. 3, the QoC_ϕ is shown for a pendulum with $T_S = 10$ and $P_{LS} \geqslant 0.9$. For each P_{LS} value, an experiment with 10^5 sampling period is repeated 10 times. Also for this case, higher values of P_{LS} indicate better performance, i.e. smaller QoC_ϕ values.

III. MODEL OF LOOP SUCCESS PROBABILITY IN IWSN

It is evident from the previous section that the Loop Success Probability dictates the QoC and also sets the delay-reliability trade-off to be achieved with lossy wireless links in the control loop. In this section, we derive the analytical model of P_{LS} for an IWSN calculating the distribution of delays in the network. The achievable network delays are specific for each communication protocol. The IWSN scenario analyzed in this paper follows the IEEE Std. 802.15.4 physical layer and the Time Slotted Channel Hopping (TSCH) medium access [22], suitable for industrial communication. TSCH provides a Time-Division Multiple Access (TDMA) scheme in combination with frequency hopping.

We model the TSCH communication resources with a TDMA frame of $2N$ time slots and an average Packet Error Rate (PER) p_e, which is determined by a specific hopping sequence in a given propagation environment. The time slots are equally shared between the two transmitters - the first N slots are allocated to the Sensor and the remaining N to the Controller. IWSN operate at low transmission powers in an interfered environment, therefore they are subject to packet loss. To increase the chance that a message is received, packet re-transmissions are needed. Let R be the maximum number of transmission attempts at both Sensor and Controller. If a packet exceeds this limit, it is dropped and no additional transmissions are attempted. Moreover, packets that exceed T_S carry outdated information that cannot be used by the NCS model of Sec. II-A. Therefore, in our system, they are automatically discarded by each transmitter.

The end-to-end delay D_{E2E} of the control loop is the sum of delays from the Sensor-to-Controller (S2C) and Controller-to-Actuator (C2A) paths

$$D_{E2E} = D_{S2C} + D_{C2A}. \tag{6}$$

The S2C and C2A delays are constituted by a stochastic buffering delay D_B and a stochastic transmission delay D_{TX}. The C2A delay additionally contains the deterministic controller processing delay D_C

$$D_{S2C} = D_B^S + D_{TX}, \tag{7}$$
$$D_{C2A} = D_B^C + D_{TX} + D_C. \tag{8}$$

As only one packet is present in the network each sampling period, buffering delay exclusively arises from the waiting time between the generation or reception of a packet and its transmission according to the schedule. The transmission delay is caused by re-transmissions in case of packet loss. For a sensor measurement generated at slot i, the buffering delays of Sensor and Controller are deterministic

$$D_B^S(i) = \begin{cases} 0, & \text{if } 1 \leqslant i < N, \\ 2N - i, & \text{if } N \leqslant i \leqslant 2N, \end{cases} \tag{9}$$

$$D_B^C(i) = \begin{cases} N - i, & \text{if } 1 \leqslant i < N, \\ 0, & \text{if } N \leqslant i < 2N, \\ N, & \text{if } i = 2N. \end{cases} \tag{10}$$

Correspondingly, the transmission delay can be modelled as a geometric r. v. with average link success probability as parameter, i.e. $D_{TX} \sim \mathrm{Ge}(1 - p_e)$. That is, the probability that the transmission delay of a packet lasts x slots starting from slot j is equal to

$$\mathrm{P}[D_{TX} = x \mid j] = p_e^{r(x,j)-1}(1 - p_e), \tag{11}$$

where $r(x,j)$ represents the number of attempts needed to achieve a transmission delay of x slots from slot j.

$$r(x,j) = \begin{cases} x, & \text{if } 0 < x \leqslant N_R(j), \\ x - (k+1)N, & \text{if } N_R(j) + (2k+1)N < x \\ & \quad \leqslant N_R(j) + 2(k+1)N, \end{cases}$$
$$k = 0,1,...,k_M,\ k_M(j) = \left\lfloor \frac{R - N_R(j) - 1}{N} \right\rfloor, \tag{12}$$

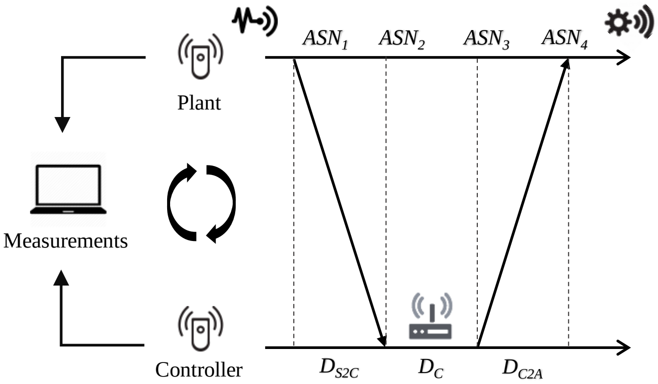

Fig. 4: Measurement setup of the network's delays.

where the delay interval in Eq. (12) defines the support of D_{TX}, and $N_R(i)$ is the number of available slots in the frame at the beginning of the transmission,

$$N_R(i) = \begin{cases} N - j \bmod 2N & \text{for the Sensor,} \\ 2N - j \bmod 2N & \text{for the Controller.} \end{cases} \tag{13}$$

The E2E delay is the sum of the buffering and transmission delays of the S2C and C2A links, which are not mutually independent. In particular, the S2C transmission delay depends on the generation of the sensor measurement, and the C2A transmission delay on both S2C transmission delay and buffering. In our analysis, we consider a stochastic arrival process A, which is characterized by arbitrary arrival probabilities for every slot in the TDMA frame. Thus, the E2E delay distribution can be calculated via conditional probabilities of the three random processes: measurement arrival, S2C transmission, and C2A transmission.

$$\begin{aligned} \mathrm{P}[D_{E2E} = y] &= \sum_{i=1}^{2N}\sum_{x=0}^{y} \mathrm{P}[A = i]\mathrm{P}[D_{S2C} = x \mid i] \\ &\quad \mathrm{P}[D_{C2A} = y - x \mid i + x] \\ &= \sum_{i=1}^{2N}\sum_{x=0}^{y} \mathrm{P}[A = i]\mathrm{P}[D_{TX} = x - D_B^S(i) \mid i + D_B^S(i)] \\ &\quad \mathrm{P}[D_{TX} = y - x - D_B^C(z) - D_C \mid z + D_B^C(z)] \\ &\overset{*}{=} \sum_{i=1}^{2N}\sum_{x=0}^{y} \mathrm{P}[A = i](1 - p_e)^2 p_e^{r\left(x - D_B^S(i), i + D_B^S(i)\right) - 1} \\ &\quad p_e^{r\left(y - x - D_B^C(z) - D_C, z + D_B^C(z)\right) - 1}, \end{aligned} \tag{14}$$

where $z = i + x + D_C \bmod 2N$, and * indicates a summation that only considers the terms where the support of D_{TX} for Sensor and Controller are defined. Therefore, the E2E delay distribution consists of a sum of exponentials weighted by the measurement arrival distribution of the sensor.

Given a sampling period T_S and the TSCH medium access parameters N, p_e and R, the P_{LS} is calculated following

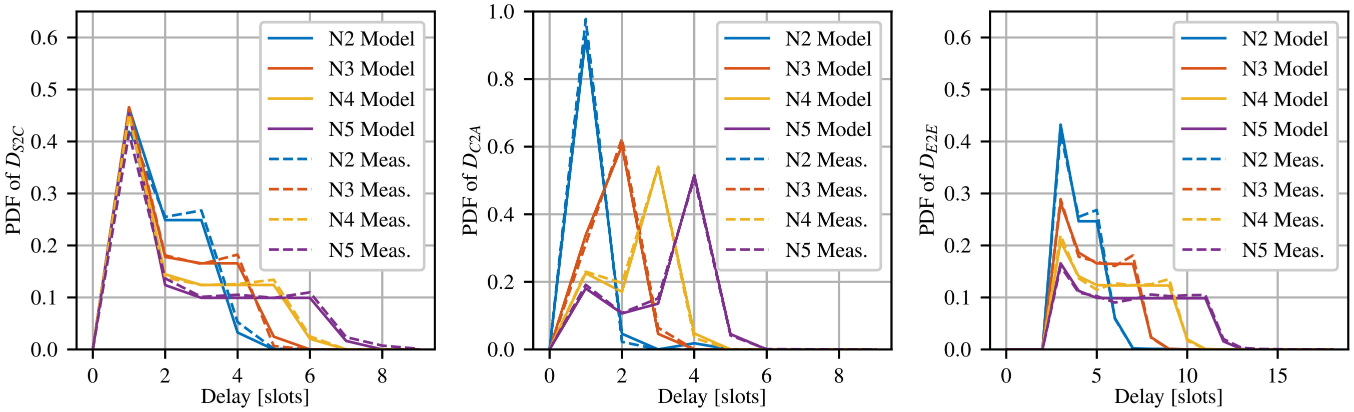

Fig. 5: S2C (left), C2A (centre) and E2E (right) analytical and measured delay distributions of different schedules for $p_e = 0.08$ and $R = 2$.

Eq. (3) as the cumulative distribution of D_{E2E}

$$P_{LS}(T_s,N,p_e,R) \overset{*}{=} \sum_{y=1}^{T_S-1}\sum_{i=1}^{N}\sum_{x=0}^{y}\mathrm{P}[A=i](1-p_e)^2 \\ p_e^{r(x-D_B(i),i)+r(y-x-D_B(i+x)-D_C,i+x)-2}, \qquad (15)$$

where the support of D_{TX} for Sensor and Controller is defined.

IV. EXPERIMENTAL VALIDATION

In order to validate the Loop Success Probability delay-reliability model and verify its relationship to QoC, we implement an IWSN testbed transmitting the messages of an emulated Inverted Pendulum. The emulated pendulum follows the dynamical model described in Sec. II-A, and performs sensing, control, and actuation following the same timing of a physical Inverted Pendulum, but in software. The emulation allows us to capture the behaviour of the system even at border conditions where a physical pendulum may not provide accurate results. The Zolertia RE-Mote™ platform is used for implementing the IWSN. The devices execute the Contiki-NG firmware, which implements the IEEE Std. 802.15.4e TSCH MAC layer. We select the NullNet network configuration of Contiki-NG, a transparent network layer with no functionalities.

Fig. 4 depicts the experimental setup used in our work. The Sensor and Controller functions are implemented, respectively, on the Plant and Controller motes, which transmit the outcome of the state evolution and control calculation of Eq. (1). As shown in Fig. 4, the motes are connected to a measurement PC that collects, for each packet, timestamps of transmission and reception in terms of Absolute Slot Number (ASN), the global time provided in TSCH. Each slot has a duration of 10 ms. For every control loop, four ASNs are recorded. ASN 1 and 2 are used to calculate the S2C delay, while 3 and 4 the C2A delay. Furthermore, ASN 2 and 3 allow us to measure the processing delay of the controller, and 1 and 4 the end-to-end delay. Measurements are affected by packet loss introduced by a common office wireless environment. The motes are transmitting at a distance of 1 m, with a transmission power of -5 dBm, and hop on channels 15, 20, 25, 26 of the 2.4 GHz ISM band.

A. *Validation Results*

Fig. 5 validates the S2C, C2A, and E2E delay distributions of Sec. III with measurements of the implemented IWSN. The nomenclature of a schedule is such that NX represents a schedule where both Plant and Controller are allocated X slots each. The results are shown for different schedules, $R = 2$ with an average link PER of $p_e = 0.08$. The sampling period of the inverted pendulum is equal to $T_S = 10$ slots and sensor's measurement arrivals are uniformly distributed in the TDMA frame, i.e. $\mathrm{P}[A = i] = T_S^{-1}, \forall i = 1,...,T_S$. Intuitively, short schedules lead to distributions that achieve smaller delays compared to large ones. For every configuration, the measurements follow the analytical curves, proving that the developed analytical model precisely characterizes the delays in the TSCH medium access.

Fig. 6 compares the P_{LS} achieved by measurement with the analytical model, for p_e values of different measurements. Also for this case, the analytical P_{LS} corresponds to the one achieved by the real system. While schedules $N2$, $N3$, $N4$ achieve a P_{LS} at which the Inverted Pendulum is stable for the entire experiment, $N5$ operates in a P_{LS} region where the pendulum in unstable. Therefore, in order to characterize the delay statistics of $N5$, measurements are collected for a stable pendulum with $T_S = 20$ slots, which achieves an experimental $P_{LS} = 0.99$, and numerically evaluated for an end-to-end delay of 10 slots to enable comparison with the other schedules.

We conclude the experimental validation by comparing the QoC_ϕ achieved in simulations with the one achieved by the emulated pendulum in the IWSN. Fig. 7 shows QoC_ϕ for different values of P_{LS} obtained performing 10 experiments of 2200 sampling periods. As expected, for a given P_{LS} achieved by the network, the pendulums achieve the same QoC_ϕ performance, proving that P_{LS} can be used to predict the achievable QoC_ϕ. In our experimental evaluation, we do

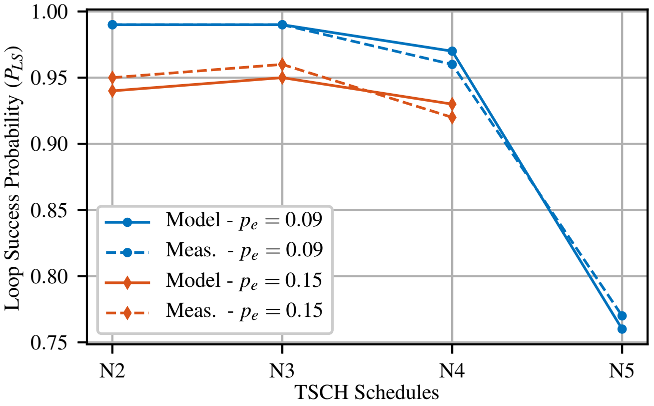

Fig. 6: Measured and analytical Loop Success Probabilities achieved by different schedules in two p_e levels for $R = 2$.

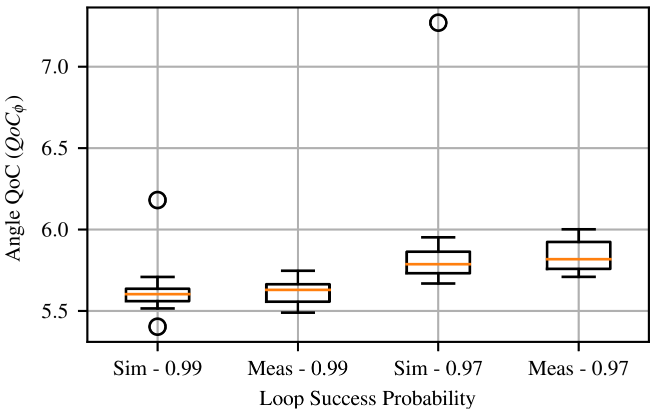

Fig. 7: Angle QoC comparison between the simulated and emulated pendulums transmitting in the IWSN.

not consider QoC_S, as the instability of the NCS makes it difficult to perform sufficiently long experiments that lead to comparable p_e. Furthermore, $QoC_S = 1$ is a necessary condition for the correct operation of the system, which can be taken into account configuring the medium access according to the proposed delay-reliability model.

We can conclude that the P_{LS}-based delay-reliability model precisely describes the experimental delays of a two-hops TSCH IWSN, and provides a direct relationship between QoC and network's performance.

V. CONCLUSION

Wireless Networked Control Systems (NCS) are a fundamental component of industrial processes in upcoming 'Smart Factories'. In order to achieve a desired Quality of Control (QoC) during their operation, an accurate model of the impact of communication errors introduced by the network is required. This has proven to be particularly challenging for IWSN, which are subject to random delays and packet dropouts arising from the harsh industrial environment.

In this work, we addressed this problem investigating the operation of an Inverted Pendulum in a two-hops TSCH IWSN. We modelled the impact of the network on the NCS in terms of Loop Success Probability (P_{LS}), the probability that a control loop is completed within the sampling period, which incorporates the delay and reliability constraints of an NCS. Furthermore, we derived the analytical model of P_{LS} for a TSCH IWSN, modelling the distribution of end-to-end delays for a TDMA medium access with frequency hopping. The model provides a connection between IWSN parameters and QoC, and is used to define the operating regions of IWSN for NCS. Finally, via measurements of an IWSN testbed and an emulated Inverted Pendulum, we evaluated the validity of the P_{LS} model and its relationship to the QoC of NCS. The measurement results proved that the proposed model precisely describes the experimental delays of a two-hops TSCH IWSN and provides a direct relationship between QoC and the network's performance.

The results of this paper open the possibility of interesting future work. In particular, given QoC constraints of the NCS, the P_{LS} model can be used to further optimize the network, for instance, to achieve energy efficiency or to share the network resources between multiple NCS. Furthermore, the packet-based analysis in this work can be used to investigate the QoC more closely, for instance, to observe the impact of individual losses and characterize their short-term effects on the NCS.

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