Channel-based Sampling Rate and Queuing State Control in Delay-Constraint Industrial WSNs

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***Abstract*—Industrial Wireless Sensor Networks (IWSNs) promote real-time data monitoring, precise control signaling transmitting and effective instrument fault diagnosing throughout manufacturing production. However, multipath attenuations, noise and co-channel interference effects may have unpredictable and time-varying impacts on the propagation channel, resulting in the failure of delivering the packets in time. To address this issue, we propose a Channel-based Sampling rate and Queuing state Control (CSQC) scheme to minimize the packet transmission delay in IWSNs. Specifically, we explore level crossing rate (LCR) to study the rapid fading characteristics of the industrial wireless propagation channel. We develop a continuous-time Markov model to evaluate the packet sojourn time and design an expectation-maximization (EM) algorithm to timely calibrate the transition rate in the model. Finally, we optimize the sensor sampling rate and queuing state to minimize the packet queuing delay in IWSNs. Simulation results show that the CSQC scheme has lower delay than IEEE 802.15.4 standard does under varying interference effects.**

I. Introduction

Industrial Wireless Sensor Networks (IWSNs) furnish the manufacturing integrated system with an automation platform which supplies information collection and transmission [1]. For example, the packaging company "Polibo" utilizes the sensor network technology to maintain quality control throughout production [2]. Versatile sensors are installed within pipes, around machines and in the workers' living area to monitor specific factors. Environmental conditions, such as air temperature around printing machines and in pipes, light intensity on the final products, and CO_2 concentration in the workers' living area, are continuously measured to keep them within authorized levels. To reduce the cost and guarantee the quality, IWSNs establish a multi-dimensional and digitalized network by flexibly monitoring the designated objects in a specific range of space [3].

To maintain the quality control throughout the production, IWSNs impose stringent transmission delay requirements on data communication between sensors and base station. Among the numerous applications of IWSNs, real-time monitoring can provide up-to-date observations for system performance evaluation. It is necessary for sensors to not only periodically send measurements to base station, but also keep the transmission delay of each measurements within limits. Moreover, in order to detect the potential risks in manufacturing production, large numbers of sensors are deployed in the environment to ensure that the measurements can be collected from numerous positions. Whereas, numerous sensors may crowd into the channel such that some sensors may fail to transmit data. Therefore, The transmission delay should be maintained to make sure that all sensors can access the channel and transmit the data in time. Furthermore, the quality of some industrial materials highly depends on the duration of exposure to the air. For example, in "Polibol" factory, the printing process during food packaging is performed by first packing the food and then printing color layer by layer on the envelop of the package until the image completes [2]. In this process, since the ink in the outlet may dry up in a short time, it is critical for sensors to feedback the packaging state as timely as possible, such that machines can finish printing without polluting the food. Hence, it is necessary to reduce transmission delay in IWSNs throughout the manufacturing production.

However, it may be difficult to significantly reduce transmission delay in the harsh industrial environment due to the following challenges. Firstly, the industrial environment is filled with multipath attenuation and interference effects. When a sensor is transmitting sampling results to the base station, its neighbors may detect a "free" channel state under the influence of the channel fading and interference. Then, they may send out their packets simultaneously, resulting in a "hidden terminal" problem. As a result, the packet queuing delay may be increased. Secondly, due to the feature of short-range transmission in IWSNs, the packet transmission delay primarily depends on the packet retransmission times and packet queuing delay. Whereas, in a time-varying industrial wireless communication scenario, it may be hard to predict packet retransmission probability in real time. Thirdly, some detailed information in the medium access control layer is invisible to the application layer such that some optimization schemes may not be applicable [4]. Meanwhile, various hidden information and time-dependent system output may degrade the accuracy of an inflexible scheme. Despite these challenges, it is possible to minimize the packet queuing delay in real time in the industrial environment.

In this paper, we propose CSQC scheme to minimize the packet queuing delay by controlling the sampling rate and queuing state in IWSNs. Specifically, our main contribution are two-fold.

- **First**, we investigate LCR to measure the rapidity of the fading in industrial wireless channel. We explore the numerical results of LCR and present an experimental closed form for practical scenario. We find that LCR is related to the envelop of the received signal and the defined distribution of envelop. Moreover, we introduce sensor sampling interval (SSI) and packet sojourn interval (PSI) to formulate the average packet queuing delay.
- **Second**, we design a continuous-time Markov model to analyze the distribution of PSI and further present a three-phase Coxian distribution to promote the calculation. Meanwhile, we propose an EM algorithm to calibrate PSI in real time. In addition, we formulate the distribution of SSI by a Weibull distribution in terms of LCR, queuing state and sampling rate, where LCR defines the distribution shape; queuing state and sampling rate define the variance and mean, respectively.

The remainder of this paper is organized as follows. The related works are present in Sec. II. The system model and problem formulation are introduced in Sec. III. Sec. IV describes the CSQC scheme. Simulation results are shown in Sec. V. Finally, we conclude this paper in Sec. VI.

II. Related Work

Numerous research efforts have been put on minimizing the packet transmission delay in the conventional WSNs [5]. They can be briefly categorized into three methods: the equivalent rate constraint approach, the Lyapunov stability drift approach and the approximate Markov decision process approach. Equivalent rate constraint approach converts the average delay constraint into an equivalent average rate one according to the large deviation theory. [6] investigates the optimal link scheduling problem in WSNs by optimizing the weight combination of effective capacity of each transmission link in terms of data rate and delay bound. Likewise, considering the max-weight of effective rate of flow on each transmission link with respect to delay constraints, [7] studies the throughput optimization problem in a fixed random access wireless multihop network, by jointly configuring the system parameters including access probability and effective transmission rate (modified by delay bound). In the Lyapunov drift approach, the constraint on delay is achieved by analyzing the stability characteristics of the proposed scheme with respect to the Lyapunov drift method. In [8], a modified max-weight-queue control policy is proposed to restrict packet queuing delay in a time-varying wireless system. This is done by using Foster Lyapunov criteria to analyze the queuing stability under the delay constraint. In [9], a delay-based Lyapunov function is investigated to achieve joint stability and utility optimization in a multiuser one-hop wireless system with time-varying reliability. This approach is further discussed in [10] in a one-hop wireless system constituted by users with or without delay constraints. In addition, the max-weight queuing policy is extended in [10] with Markov Decisions associated with delay constraints using Lyapunov drift and Lyapunov optimization theory. In the Markov decision process, the system state is characterized by the aggregation of the channel state information and queuing state information. [11] proposes an average reward constraint Markov decisions model to optimize the lifetime of sensor nodes under the delay constraint while minimizing the weighted packet loss rate in IWSNs.

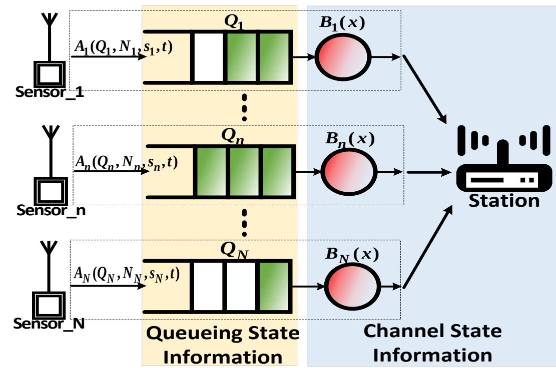


Fig. 1: Network Model

Different from the existing works, we propose a CSQC scheme to minimize the packet queuing delay by configuring the sampling rate and queuing state. The proposed scheme can exploit the characteristics of the fading channel in industrial environment and modify parameters in real time.

III. System Model and Problem Formulation

A. Network Model

IWSNs are deployed in the industrial environment filled with multipath attenuation, noise and interference effects, as shown in Fig. 1. We consider a one-hop wireless network, which consists of N sensors and one base station. Sensors are equipped with sensing devices to measure the ambient environment. The base station and sensors associate with each other according to the IEEE 802.15.4 standard. The sensor monitors the environment based on the sampling rate and further stores the measurement data in the queue for transmission. Let $\boldsymbol{A}(\boldsymbol{Q}, \boldsymbol{N}, \boldsymbol{s}, t) = (A_1(Q_1, N_1, s_1, t), \ldots, A_N(Q_N, N_N, s_N, t))$ be the process of random packet arrivals, where $A_n(Q_n, N_n, s_n, t)$ is an arbitrary distribution regarding to SSI of sensor n, where s_n is the sampling rate. For simplicity, PSIs are also drawn from an arbitrary distribution given by $\boldsymbol{B}(t) = (B_1(t), \ldots, B_N(t))$. The PSI distribution $B_n(t)$ is related to the observations of packet sojourn time. Let $\boldsymbol{Q}(t) = (Q_1(t), \ldots, Q_N(t))$ is the integer number of packets currently stored in each of the N queues and $\boldsymbol{N}(t) = (N_1(t), \ldots, N_N(t))$ be the fading characteristics of the industrial channel.

Our objective is to minimize the packet queuing delay by modifying the sampling rate and queuing state according to the analysis of the channel features and the packet sojourn time in real time.

B. Channel State Information

In IWSNs, the received signal often undergoes heavy statistical fluctuations which leads to not only a dramatic increase of the bit error rate, but also “hidden” terminal problem. The change of the signal-to-noise ratio (SNR) is mostly used to study the channel state. However, SNR only describes the strength of the received signal but not the variation of the propagation channel. Hence, in order to predict the probability of accessing channel and calibrating the rate to transmit data, it is important to investigate the crossing rate of the received signal to cross a given signal level per time unit. Now, we study LCR to describe this statistic characteristics of fading channels. We describe the probability density function of the received signal envelop crossing a given level R in a positive direction as LCR, which is denoted as $N_r(R)$ [12]. $N_r(R) = \int_0^\infty \dot{x} p_{r\dot{r}}(R, \dot{x}) d\dot{x}$, where $R \geq 0$ and $p_{r\dot{r}}(x, \dot{x})$ is the joint density function of the received signal envelop and its time derivative $\dot{r}(t)$ at the same time instant.

We consider a line of sight propagation scenario (there is a direct predominant path over the indirect ones) in the industrial environment with deterministic co-channel interference from the neighbor sensors. Let the transmitted signal be $s(t) = p\exp(jw_0 t)$. The received signal by a sensor in an industrial environment with multipath propagation may be given as $r(t) = r\exp[j(w_0 t + \theta)]$. If there is a line-of-sight propagation, the received signal can be further modified as $\exp(jw_0 t)[p_0 \exp(j\theta_0) + \sum_{n\in\{1...n\}} p_n \exp(j\theta_n)]$, where $\theta_n = w_n t = 2\pi f_n t$. Considering co-channel interference which follows Rayleigh distribution, we investigate signal-to-interference ratio $\frac{r(t)}{I(t)}$ to determine the quality of received signal, where $I(t) = \sum_{n\in\{1,...,n\}} I_n \exp(j\phi_n)$, where $\phi_n = v_n t$. S protection ratio k is required for reliable reception, i.e., $\frac{r(t)}{I(t)} \geq k$. When $r(t) \leq kI(t)$, significant transmission errors are expected. Therefore, we substitute the giving level R with $r(t) - kI(t)$ and further modified the received signal as $p_0 \exp(j\theta_0) + \sum_{n\in\{1...n\}} p_n \exp(j\theta_n) - k\sum_{n\in\{1,...,n\}} I_n \exp(j\phi_n)$. We simplify this expression as $Q + \sum_{n\in\{1...n\}} p_n \exp(j\theta_n) - \sum_{n\in\{1,...,n\}} g_n \exp(j\phi_n)$. Using the Euler's Identities, we have $I_c = \sum_n x_1 + \ldots + x_N = r\cos\theta - Q$ and $I_s = \sum_n y_1 + \ldots + y_N = r\sin\theta$, where

$$I_c = \sum_n p_n \cos(w_n - q)t - g_n \cos(v_n - q)t \quad (1)$$

$$I_s = \sum_n p_n \sin(w_n - q)t - g_n \sin(v_n - q)t \quad (2)$$

where we employ a phase component in the expression to present the burst variation from vibrating object or impulse noise. We modify (1) and (2) to have the expression of x_n and y_n as $x_n = (p_n - A_c)\cos(w_n - q)t + A_s \sin(w_n - q)t$ and $y_n = (p_n - A_c)\sin(w_n - q)t + A_s \cos(w_n - q)t$, respectively, where $A_c = g_n \cos(v_n - w_n)t$ and $A_s = g_n \sin(v_n - w_n)t$. In addition, we define the time derivatives of $\dot{x}_n$ and $\dot{y}_n$ as

$$\dot{x}_n = (w_n - q)[\dot{A}_s \cos(w_n - q)t - (p_n - \dot{A}_c)\sin(w_n - q)t]$$
$$\dot{y}_n = (w_n - q)[(p_n - \dot{A}_c)\cos(w_n - q)t - \dot{A}_s \sin(w_n - q)t]$$

where $\dot{A}_s = -(v_n - w_n) g_n \sin(v_n - w_n)t$ and $\dot{A}_c = (v_n - w_n) g_n \cos(v_n - w_n)t$. In order to find the joint density function of the received signal envelop and its time derivatives, we calculate the covariance based on the linearity property of expectations $cov(X, Y) = E[XY] - E[X]E[Y]$. We further substitute the results into (1) and (2) and summary them in Table. I. Hence, the probability that the the received signal envelop passes through the value R during the interval $t, t+dt$ with positive slope is $dt \int_0^\infty \dot{r} p(r, \dot{r}, t) d\dot{r}$. We show the covariance matrix and its moment matrix in (3). The time derivatives of I_c and I_s can be defined as $\dot{I}_c = \dot{r}\cos\theta - r\sin\theta\dot{\theta}$, $\dot{I}_s = \dot{r}\sin\theta + r\cos\theta\dot{\theta}$ and $dI_c dI_s d\dot{I}_c d\dot{I}_s = r^2 dr d\dot{r} d\theta d\dot{\theta}$. The moment matrix and covariance matrix are

TABLE I: Expectation Results

Expression	Value	Label
$E\{I_c\}, E\{I_s\}$	0	
$E\{\dot{I}_c\}, E\{\dot{I}_s\}$	0	
$E\{I_c^2\}, E\{I_s^2\}$	$\frac{1}{2n}\sum_n E\{p_n^2 + g_n^2\}$	b_0
$E\{\dot{I}_c^2\}, E\{\dot{I}_s^2\}$	$\frac{1}{2n}\sum_n (w_n - q)E\{p_n^2 + (v_n - w_n)^2 g_n^2\}$	b_2
$E\{I_c I_s\}, E\{\dot{I}_c \dot{I}_s\}$	0	
$E\{I_c \dot{I}_c\}, -E\{I_s \dot{I}_s\}$	$\frac{1}{2n}\sum_n (w_n - q)E\{-g_n^2(v_n - w_n)\}$	a_1
$E\{I_c \dot{I}_s\}, -E\{I_s \dot{I}_c\}$	$\frac{1}{2n}\sum_n (w_n - q)E\{p_n^2\}$	a_2

$$\boldsymbol{A} = \begin{pmatrix} I_c^2 & I_c I_s & I_c \dot{I}_c & I_c \dot{I}_s \\ I_s I_c & I_s^2 & I_s \dot{I}_c & I_s \dot{I}_s \\ \dot{I}_c I_c & \dot{I}_c I_s & \dot{I}_c^2 & \dot{I}_c \dot{I}_s \\ \dot{I}_s I_c & \dot{I}_s I_s & \dot{I}_s \dot{I}_c & \dot{I}_s^2 \end{pmatrix} \quad \boldsymbol{M} = \begin{pmatrix} b_0 & 0 & a_1 & a_2 \\ 0 & b_0 & -a_2 & -a_1 \\ a_1 & -a_2 & b_2 & 0 \\ a_2 & -a_1 & 0 & b_2 \end{pmatrix} \quad (3)$$

We define the inverse of matrix $\boldsymbol{M}$ as $\boldsymbol{M}^{-1} = \text{adj}(\boldsymbol{M})/\det(\boldsymbol{M}) = \Lambda/B$, which enables us to write the probability density function of r, $\dot{r}$, θ and $\dot{\theta}$ as $p(r, \dot{r}, \theta, \dot{\theta}) = \frac{R^2}{4\pi^2 B}\exp\left(-\frac{1}{2B}\sum_{i,j} A_{i,j}\Lambda_{i,j}\right)$. In the expression that θ is from $-\pi$ to π and $\dot{\theta}$ is from $-\infty$ to ∞, we show the density function for r and $\dot{r}$ is $p(r, \dot{r}) = \frac{r^2}{4\pi^2 B}\int_0^{2\pi}\int_{-\infty}^{\infty}\exp\left(-\frac{1}{2B}\sum_{i,j} A_{i,j}\Lambda_{i,j}\right) d\dot{\theta} d\theta$. In the end, $N_r(R)$ can be further simplified as $\sqrt{b_0/(2\pi)}p(r)$, where b_0 is the expectation value of the received power gain from each path, $p(r)$ is the probability density function (pdf) of the envelop of the received signal.

C. Problem Formulation

We consider that SSI is independent with each other. The distribution of SSI is denoted as $A_n(Q_n, R_n, s_n, t)$. PSIs are also independently drawn from an arbitrary distribution given by $B_n(x)$. As shown in Fig. 1, there is one base station in the system and the queue in each sensor is offered in a first come first served order. We consider a sequence of sampling results comes into the queue which is indexed by the subscript m. We define C_m as the mth sampling results arriving to the system; $t_m = \tau_m - \tau_{m-1}$ as the interarrival time between C_{m-1} and C_m; b_m as PSI to transmit C_m and w_m as queuing delay (waiting in queue) for C_m. We assume that the random variables $\{t_m\}$ and $\{x_m\}$ are independent and are defined by the distribution of $A_n(Q_n, R_n, s_n, t)$ and $B_n(x)$.

The waiting time w_m can be considered in two cases: 1). C_{m+1} arrives to the system before C_m departs from the queue; 2). C_{m+1} arrives to an empty system. Hence, w_{m+1} equals $w_m + x_m - t_{m+1}$, when $w_m + x_m - t_{m+1} \geq 0$; otherwise, equals 0. For convenience we define a new random variable u_m as $u_m \triangleq x_m - t_{m+1}$. Substituting w_{m+1} with u_m, we have $w_{m+1} = u_m$ when $w_m + u_m \geq 0$; otherwise, equals 0. We can further write w_{m+1} as $w_{m+1} = \max[0, w_m + u_m] = (w_m + u_m)^+$. The stationary distribution of w_m is defined as $\lim_{m\to\infty} P[w_m \leq y] = W(y)$, which exists when $E[u_m] <$

0. We define $G_m(u)$ as the probability distribution function (PDF) for the random variable u_m, $G_m(u) \triangleq P[u_m = x_m - t_{m+1} \leq u]$. We derive the expression for $G_m(u)$ in terms of $A_n(Q_n, R_n, s_n, t)$ and $B_n(x)$ as

$$\begin{aligned} G_m(u) &= P[x_m - t_{m+1} \leq u] \\ &= \int_{t=0}^{\infty} P[x_m \leq u + t | t_{m+1} = t] dA_n(Q_n, R_n, s_n, t) \\ &= \int_{t=0}^{\infty} B_n(u+t) dA_n(Q_n, R_n, s_n, t) = C(u) \quad (4) \end{aligned}$$

Since $W_m(y) = P[w_m \leq y]$, for $y \geq 0$, the PDF of w_{m+1} is

$$\begin{aligned} W_{m+1}(y) &= P[w_m + u_m \leq y] \\ &= \int_{0^-}^{\infty} P[u_m \leq y - w | w_m = w] dW_m(w) \quad (5) \end{aligned}$$

where $P[u_m \leq y - w | w_m = w] = G_m(y - w)$ since u_m is independent of w_m. The limiting PDF is $W(y) = \int_{0^-}^{\infty} C(y - w) dW(w)$, for $y \geq 0$; otherwise, equals 0. Combining these two descriptions, we have the *Lindley's integral equation* that $W(y)$ equals $\int_{0^-}^{\infty} C(y - w) dW(w)$ when $y \geq 0$; otherwise, equals 0. Integrating by parts, for $y \geq 0$, $W(y)$ can be further written as $W(y) = C(y - w)W(w)|_{w=0}^{\infty} - \int_{0^-}^{\infty} W(w) dC(y - w)$. Considering the simple variable change $u = y - w$ for the argument of the PSI distribution, we define that

$$W(y) = \begin{cases} \int_{u=-\infty}^{y} W(y-u) dC(u) & y \geq 0 \\ 0 & y < 0. \end{cases} \quad (6)$$

Define a "complementary" PSI distribution

$$W_-(y) \triangleq \begin{cases} 0 & y \geq 0 \\ \int_{u=-\infty}^{y} W(y-u) dC(u) & y < 0. \end{cases} \quad (7)$$

Combining (6) and (7), $W(y) + W_-(y) = \int_{-\infty}^{y} W(y - u) c(u) du$, where we define the probability density function (pdf) of $\tilde{u}$ as $g(u) \triangleq dG(u)/du$. In order to derive the packet queuing delay distribution from the determined harvesting interval and free channel detection interval distribution, we employ Laplace transform to simplify this investigation. We denote the Laplace transform of $W_-(y)$ and $W(y)$ as $\Phi_-(s) \triangleq \int_{-\infty}^{0} W_-(y) e^{-sy} dy$ and $\Phi_+(s) \triangleq \int_{0^-}^{\infty} W(y) e^{-sy} dy$, respectively. Note that $\Phi_+(s)$ is the Laplace transform of the PDF for packet queuing delay. Let $W^*(s)$ be the transform for the queuing time such that we have $s\Phi_+(s) = W^*(s)$. Since we define the pdf of u as $g(u) = dG(u)/du = a(-u) \otimes b(u)$, $C_m^*(s) = A_n^*(Q_n, R_n, s_n, -s) B_n^*(s)$. Taking the Laplace transform of $W(y) + W_-(y)$, we have $\Phi_+(s) + \Phi_-(s) = \Phi_+(s) C_n^*(s) = \Phi_+(s) A_n^*(Q_n, R_n, s_n, -s) B_n^*(s)$ which gives us $\Phi_-(s) = \Phi_+(s)[A_n^*(Q_n, R_n, s_n, -s) B_n^*(s) - 1]$. We introduce a rational function of s and substitute into Φ_- that $\Phi_-(s) = \Phi_+(s) \frac{\Psi_+(s)}{\Psi_-(s)}$. Applying the *Liouville's Theorem*, we have $\Phi_-(s)\Psi_-(s) = \Phi_+(s)\Psi_+(s) = K$, which yields that $\Phi_+(s) = \frac{K}{\Psi_+(s)}$. Since $s\Phi_+(s) = W^*(s)$, we have $s\Phi_+(s) = W^*(s) \triangleq \int_{0^-}^{\infty} e^{-sy} dW(y)$. We have $\lim_{s \to 0} \int_{0^-}^{\infty} e^{-sy} dW(y) = \int_{0^-}^{\infty} dW(y)$. The $W^*(s)$ can be further written as

$$\int_{0^-}^{\infty} dW(y) = \lim_{s \to 0} s\Phi_+(s) = \lim_{s \to 0} \frac{sK}{\Psi_+(s)} = 1 \quad (8)$$

where $K = \lim_{s \to 0} \frac{\Psi_+(s)}{s}$.

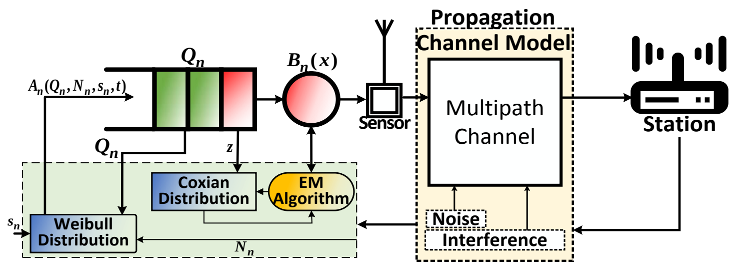


Fig. 2: Overview of the Proposed Scheme

We summarize the method to calculate the packet queuing delay as $Z(\cdot)$ as: **1**) we use $A_n^*(Q_n, R_n, s_n, -s) B_n^*(s) - 1 = \frac{\Psi_+(s)}{\Psi_-(s)}$ to determine $\Psi_+(s)$ and $\Psi_-(s)$; **2**) we determine K by $\lim_{s \to 0} \frac{\Psi_+(s)}{s}$; **3**) we determine $\Phi_+(s)$ by $\frac{K}{\Psi_+(s)}$; **4**) we use $s\Phi_+(s) = W^*(s)$ to find the Laplace transform for the pdf for w; and finally we obtain $W(y)$ by $\mathcal{F}^{-1} W^*(s)(y)$.

The objective is to minimize the packet queuing delay by controlling the sampling rate s_n and queuing state Q_n for each node n over a period. According to the aforementioned packet queuing delay in terms of the distribution of SSI and PSI, we define Weibull distribution as the SSI distribution in our queuing model with three parameters, $A_n(Q_n, R_n, s_n, t) = \frac{R_n}{Q_n} (\frac{t - s_n}{Q_n})^{R_n - 1} \exp(-\frac{t - s_n}{Q_n})^{R_n}$, where R_n is the shape parameter, Q_n is the scale parameter and s_n is the location parameter. The packet queuing delay can be formulated as

$$\begin{aligned} &\underset{\boldsymbol{Q}, \boldsymbol{s}}{\text{argmin}} \quad W(y|\boldsymbol{Q}, \boldsymbol{s}) \\ &\text{subject to } W(y|\boldsymbol{Q}, \boldsymbol{s}) = Z(A_n^*(Q_n, R_n, s_n, -s), B_n^*(s)) \end{aligned} \quad (9)$$

where $Z(\cdot)$ is the process to obtain the packet queuing distribution.

IV. The Proposed CSQC Scheme

As shown in Fig. 2, the CSQC scheme is proposed by firstly determining LCR on the basis of received signal envelope; secondly investigating the PSI distribution based on the observed sojourn time that the packet waits on the head of the queue for detecting free channel to transmit; thirdly employing EM algorithm to derive the PSI distribution from the Coxian distribution. The SSI distribution is derived from the Weibull distribution in terms of LCR, queuing state information and sampling rate. We solve the minimization problem in (9) to configure the sampling rate and queuing state such that the packet queuing delay can be restricted in a limitation.

According to the delay tapped channel model in [3], we define the received signal in (12), where $A_m(t)$ is the power gain factor, τ_m is the delay effect caused by the m-th scatter at time t, f_m is the m-th Doppler effect and ϕ_{D_m} is the phase variation. The received signal is composed by multipath components and primary component, which can be further separated into real and imaginary parts. Assuming that $h_{\mu_1}(t)$ and $h_{\mu_2}(t)$ are statistically independent, we denote the joint probability density function of the two parts as $p_h = p_{(h_{\mu_1} + h_{\rho_1})}(x_1) \cdot p_{(h_{\mu_2} + h_{\rho_2})}(x_2)$. Considering polar coordinated (z, θ) by means of $x_1 = zcos(\theta), x_2 = zsin(\theta)$,

$$h(t) = \sum_{m=0}^{M} A_m(t - \tau_m(t)) \cdot \exp\Big(j(2\pi f_c \tau_m(t) - \phi_{D_m}(t))\Big) \tag{11}$$
$$= h_{\mu_1}(t) + h_{\rho_1}(t) + j(h_{\mu_2}(t) + h_{\rho_2}(t))$$
$$= \sum_{m=1}^{M} \alpha_m \cos(2\pi f_m t - \phi_{D_m}) + \alpha_0 \cos(2\pi f_0 t - \phi_{D_0}) + j\Big(\sum_{m=1}^{M} \alpha_m \sin(2\pi f_m t - \phi_{D_m}) + \alpha_0 \sin(2\pi f_0 t - \phi_{D_0})\Big) \tag{12}$$
$$p_\xi(z) = z\int_{-\pi}^{\pi} p_{h_{\mu_1}}(zcos(\theta) - \alpha_0 cos\phi_{D_m}) \cdot p_{h_{\mu_2}}(zsin(\theta) - \alpha_0 sin\phi_{D_m})d\theta$$
$$= 4\pi z \int_0^{\pi}\int_0^{\infty}\left[\prod_{m=1}^{M} J_0(2\pi\alpha_m y cos\theta)\right]\left[\prod_{m=1}^{M} J_0(2\pi\alpha_m y sin\theta)\right] J_0(2\pi z y)cos[2\pi\alpha_0 y cos(\theta - \phi_{D_m})]ydyd\theta \tag{13}$$

Algorithm 1: EM Algorithm for Service Time Distribution

Data: Trace data $\mathcal{T} = t_1, \ldots, t_m$
Result: Service time distribution $B(\boldsymbol{\pi}, \boldsymbol{D}_0)$
Randomly Initialize $\hat{\boldsymbol{\pi}}, \hat{\boldsymbol{D}}_0$
repeat
  for *each* $k \in \{1, \ldots, m\}$ **do**
    $a(y_k|\boldsymbol{\pi}, \boldsymbol{D}_0) = \hat{\boldsymbol{\pi}} \exp(\hat{\boldsymbol{D}}_0 y_k)$,
    $b(y_k|\boldsymbol{\pi}, \boldsymbol{D}_0) = \exp(\hat{\boldsymbol{D}}_0 y_k)\hat{\boldsymbol{d}}_1$
    $c(y_k|\boldsymbol{\pi}, \boldsymbol{D}_0) = \int_0^{y_k} a(y_k - u|\boldsymbol{\pi}, \boldsymbol{D}_0)e_i b(u|\boldsymbol{\pi}, \boldsymbol{D}_0)du$
  end
  $E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[B_i] \leftarrow \frac{1}{m}\sum_{k=1}^{m} \frac{\boldsymbol{\pi}(i)a(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)(i)}{\boldsymbol{\pi}b(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)}$
  $E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[Z_i] \leftarrow \frac{1}{m}\sum_{k=1}^{m} \frac{b(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)(i,i)}{\boldsymbol{\pi}b(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)}$
  $E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[N_{ij}] \leftarrow \frac{1}{m}\sum_{k=1}^{m} \frac{\boldsymbol{D}_0(i,j)c(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)(i,j)}{\boldsymbol{\pi}b(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)}$
  $E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[N_{in+1}] \leftarrow \frac{1}{m}\sum_{k=1}^{m} \frac{\boldsymbol{d}_1(i)a(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)(i)}{\boldsymbol{\pi}b(y_k|\boldsymbol{\pi},\boldsymbol{D}_0)}$
  $\hat{\boldsymbol{\pi}} \leftarrow E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[B_i]$, $\hat{\boldsymbol{D}}_0(i,j) \leftarrow \frac{E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[N_{ij}]}{E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[Z_i]}$
  $\hat{\boldsymbol{d}}_1(i) \leftarrow \frac{E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[N_{in+1}]}{E_{(\boldsymbol{\pi},\boldsymbol{D}_0)|\mathcal{T}}[Z_i]}$,
  $\hat{\boldsymbol{D}}_0(i,i) \leftarrow -\Big(\hat{\boldsymbol{d}}_1(i) + \sum_{i\neq j,j=1}^{n} \hat{\boldsymbol{D}}_0(i,j)\Big)$
until $\|\boldsymbol{\pi} - \hat{\boldsymbol{\pi}}\| + \|\boldsymbol{D}_0 - \hat{\boldsymbol{D}}_0\| < \epsilon$
Output: Service time distribution $B(\hat{\boldsymbol{\pi}}, \hat{\boldsymbol{D}}_0)$

The joint pdf $p_{r\vartheta}(z, \theta)$ of the received signal envelop can be written as

$$p_{\xi\vartheta}(z, \theta) \tag{10}$$
$$= zp_{(h_{\mu_1}+h_{\rho_1})}(zcos(\theta)) \cdot p_{(h_{\mu_2}+h_{\rho_2})}(zsin(\theta))$$
$$= p_{h_{\mu_1}}(zcos(\theta) - \alpha cos\phi_{D_m}) \cdot p_{h_{\mu_2}}(zsin(\theta) - \alpha sin\phi_{D_m})$$

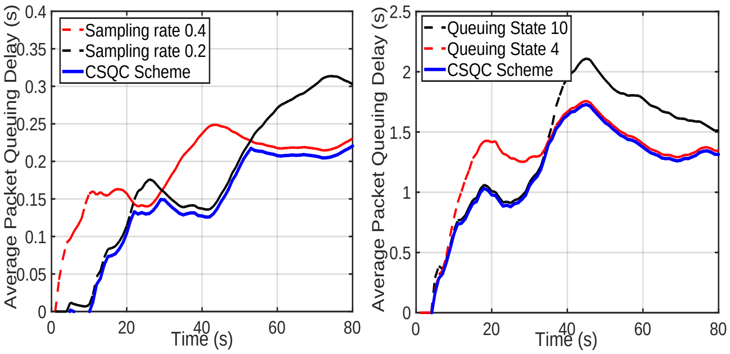
Hence, after some algebraic manipulation we show the pdf of the received signal envelop in (13). We can also define LCR according to the analysis in Sec. III-B as $N_\xi(r) = \sqrt{\frac{-\ddot{r}_{\mu_i\mu_i}(0)}{2\pi}} p_\xi(z)$, where $-\ddot{r}_{\mu_i\mu_i}(0) = \frac{1}{2}\sum_{n=1}^{N_i}(c_{in}2\pi f_{in})^2$, c_{in} is the square of the autocorrelation of the received signal.

$$\boldsymbol{D} = \left(\begin{array}{ccc|c} -\lambda_1 & g_1\lambda_1 & 0 & (1-g_1)\lambda_1 \\ 0 & -\lambda_2 & g_2\lambda_2 & (1-g_2)\lambda_2 \\ 0 & 0 & -\lambda_3 & \lambda_3 \\ \hline 0 & 0 & 0 & 0 \end{array}\right) \tag{14}$$

According to IEEE 802.15.4 standard, sensors randomly initial a backoff time and scan the channel until the backoff time turns to zero. If sensors find a busy channel, they generate a new backoff time. Sensors access into the channel when they scan a free channel. If sensors do not receive any ACK messages, they will retransmit the packets until the maximum retry limit which is set as 3 times. In order to find the free channel detection interval distribution, the performance of average sojourn time distribution should be evaluated. However, conventional Markov model for sojourn time analysis is too heavy for the sensors to timely investigate the FCD interval distribution. In addition, since only the observations of time till absorption state, $t_i \in \mathcal{T}$, $i = 1, \ldots, m$, can be easily obtained, the background Markov process remains unobserved in the sense that there are no information how the Markov process entered into the absorption phase and sojourn time it stays in each phase. EM algorithm is employed to investigate the parameters in this hidden problem. Hence, in order to exploit the FCD interval distribution, we introduce Coxian distribution with sojourn time information in each transition state to estimate the FCD interval distribution by means of EM fitting algorithm. Considering 3 retransmission state and 1 absorbing state, we define $\{X(t)\}_{t\geq 0}^{\infty}$ as a stochastic process in this state space. Since a packet will always start from the first state, we let the initial distribution vector to be $\boldsymbol{\pi} = [1, 0, 0, 0]$ After starting in phase 1 the process traverses through 3 unsuccessive phases with possibility different rates λ_i. From the phase i the transition to the next phase $i+1$ can occur with probability g_i or the absorbing state is reached with the complementary probability $1 - g_i$. The transition matrix of the deterministic Coxian distribution is shown in (14). The generator matrix $\boldsymbol{D}$ can be further expressed as $\boldsymbol{D} = \left(\begin{array}{c|c} \boldsymbol{D}_0 & d \\ \hline \boldsymbol{0} & 0 \end{array}\right)$, where $d = -\boldsymbol{D}_0\boldsymbol{e}$, $\boldsymbol{e} = (1, \ldots, 1)^T$. We denote the density function of this Coxian distribution as $f(y) = \boldsymbol{\pi}\exp(\boldsymbol{D}_0 y)d$. Observation $t_i \in \mathcal{T}, i = 1, \ldots, m$, of the time till absorption are the incomplete observation of the Markov process $\{X(t)\}_{0\leq t<t_i}$. We denote the whole stochastic process till absorption state as $X_0, \ldots, X_{k-1}$ and further denote the corresponding sojourn time as $s_0, \ldots, s_{k-1}$. Thus, given an observation y of the Coxian distribution, a complete observation of the process $\{X(t)\}_{0\leq t<t_i}$ can be represented by $z = (x_0, \ldots, x_{k-1}, s_0, \ldots, s_{k-1})$, where the time to the absorption state must satisfy $t_i = s_0 + \ldots + s_k$. Since the pdf of the complete observation z is $f(z|\boldsymbol{\pi}, \boldsymbol{D}_0)$, we define the likelihood function as

$$\mathcal{L}((\boldsymbol{\pi}, \boldsymbol{D}_0)|\mathcal{T}) = \tag{15}$$
$$= \prod_{i=1}^{n} \boldsymbol{\pi}(i)^{B_i} \prod_{i=1}^{n} \exp(Z_i\boldsymbol{D}_0(i,i)) \prod_{i=1}^{n}\prod_{j=1,j\neq i}^{n+1} \boldsymbol{D}_0(i,j)^{N_{i,j}}$$

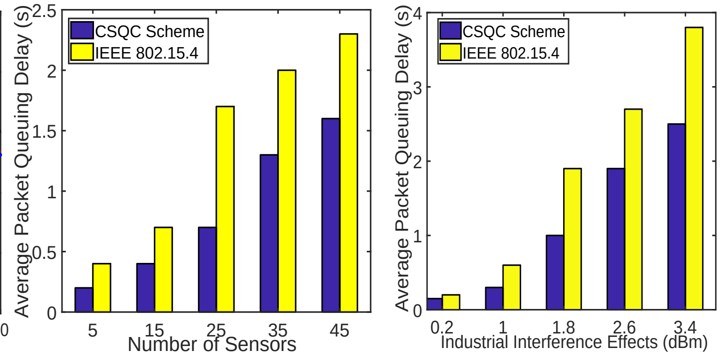
where the amount of times the system started in state i is denoted by B_i, the waiting time stay in state i is given by Z_i, and the total observed number of jumps from state i to j is N_{ij}, for $i \neq j$. The details of the parameters exploiting in the



(a) CSQC with Configuring Sampling Rate

(b) CSQC with Configuring Queuing State

Fig. 3: The Normalized Packet Queuing Delay vs. Time



(a) APQD vs. Number of Sensors

(b) APQD vs. Interference Effects

Fig. 4: The Impacts of the Number of Sensors and Interference

FCD interval distribution based on EM algorithm is proceeds in Alg. 1.

V. Performance Evaluation

We evaluate the performance of the proposed CSQC scheme on OMNET++. The network consists of five sensors and one base station. The network topology is shown in Fig. 1. The performance of the CSQC scheme over time is shown in Fig. 3a. In the case where the PSI distribution is artificially changed over time, we define two sampling rates to study whether our scheme can select corresponding sampling rate towards the lower queuing delay. The figure shows that the sampling rate related to the lower delay can be found. A deterministic simulation on queuing state is further shown in Fig. 3b. The CSQC scheme can select the queuing state that provides a better queuing delay solution.

Fig. 4 shows the comparison of the normalized packet queuing delay between the proposed scheme and IEEE 802.15.4 standard does by changing the number of sensors and the sum of the noise and interference effects. In Fig. 4a, the packet queuing delay increases with the rising number of sensors. More sensors increase the contention probability and further enlarge the interval to detect a free channel, resulting in an increasing PSI. In addition, the proposed CSQC scheme provides a lower packet queuing delay than IEEE 802.15.4 standard when the number of sensors increases in the industrial environment. Fig. 4b shows the comparison results by magnifying the effects of interference. Compared with the IEEE 802.15.4 standard, the packet queuing delay of the proposed CSQC scheme is reduced by considering a minimization framework in terms of QSI and CSI. The channel characteristics is further investigated by LCR, which enables the CSQC scheme to minimize packet queuing delay through the evaluation on the fading channel in the industrial environment.

VI. Conclusion

In this paper, we have proposed a CSQC scheme to minimize packet queuing delay by controlling the sampling rate and queuing state of the sensor with the knowledge of channel state and packet sojourn interval. Specifically, we have studied LCR to analyze the specific characteristic of the industrial channel. We have proposed the SSI distribution model which is built on the configuration of the Weibull distribution in terms of LCR, QSI and sampling rate. PSI has been further investigated by considering a three-phase Coxian distribution model which is iteratively calibrated by EM algorithm. Simulation results show that the proposed CSQC scheme can provide lower packet queuing delay than IEEE 802.15.4 standard. For the future work, we will study the average fading duration of the industrial channel model with an attempt that the sensors can predict the sampling rate and queuing state to further minimize queuing delay.

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