D2D Transmission Scheme in URLLC Enabled Real-Time Wireless Control Systems for Tactile Internet

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***Abstract*—Ultra-reliable and low-latency communication (URLLC) is promising to enable real-time wireless control systems for tactile internet. In such a system, it is difficult to maintain extremely high quality-of-service (QoS) in URLLC for real-time control. In this paper, we develop a probability-based device-to-device (D2D) scheme to deal with this issue, where communication and control are jointly considered. In our scheme, the transmitters autonomously decide whether to be active to participate in the control process of the receiver based on a certain probability, which can significant reduce the interacting communication latency between them, lower the transmission power consumption, and improve communication reliability. Compared with traditional D2D transmission method, simulation results show remarkable performance gain of our method.**

I. Introduction

Ultra-reliable and low-latency communication (URLLC) is an important scenario to support real-time wireless control systems for tactile internet [1][2]. To maintain both stringent communication reliability and low latency for good control performance, we intend to adopt device-to-device (D2D) communications since it can significantly reduce power consumption, lower transmission latency, and improve reliability [3]–[5]. However, there are two critical challenges that should be solved in such a system.

The first key challenge in D2D communications is D2D pair activation, which can be cellular assisted or autonomous [6]. The cellular assisted method can sufficiently uses the device information at the base station (BS) to determine the D2D pair match. However, the signaling overhead leads to high communication latency. In traditional autonomous method, the devices need to transmit reference signals to deal with the D2D pair match, where this method is extremely challenging for URLLC since the devices are mainly battery powered. In summary, it is extremely difficult to schedule D2D pairs by existing method due to communication constraints in URLLC.

The second key challenge is to obtain good overall system performance by jointly considering D2D in URLLC and control. There are some research on wireless control systems from control perspective [8]–[10]. However, these research are based on the existing wireless communication protocols, which cannot guarantee the QoS requirements in URLLC for real-time wireless control systems.

In this paper, we propose a new autonomous D2D transmission method to deal with the above two challenges in URLLC for real-time wireless control systems, where both communication and control are jointly considered. In particular, we formulate an optimal problem to minimize transmission power consumption under constraints of URLLC and control. To solve the problem, we first analyze the relationship between control and communication, where we find that the control constraint can be converted into the constraint on communication reliability. Then, we propose a probability-based D2D activation method, which allows each transmit device autonomously decide whether to participate the control process and optimizes the power consumption while guaranteeing the stringent requirements in URLLC for real-time wireless control systems.

The rest of this paper is organized as follows. In Section II, the system model is presented. In Section III, the optimal problem with both communication and control constraints is formulated. In Section IV, we obtain the optimal probability-based activation method and transmission power allocation method. In Section V, simulation results are provided to show the performance. Finally, Section VI concludes the paper.

II. System Model

As shown in Fig. 1, we consider a wireless control model that M independent sensors intend to serve a plant[1] by direct D2D communications. In such a control process, each active sensor samples the plant state and transmits it to the controller inside the plant via wireless channel. Then, the controller chooses the strongest signal as its desired signal and calculates the control command and sends the command to the actuator to update plant's current state. In this section, the system model considering both communication latency and reliability is presented for the performance evaluation in real-time wireless control systems.

A. Communication

In this subsection, we provide communication sub-system model with transmission latency and packet error probability in URLLC. As shown in Fig. 1 (a), M potential transmit devices are the sensors uniformly distributed in a certain circle region with radius R, and the receive device is the controlled plant in the center of the region. Here, each sensor is activated based on a certain probability. In addition, the plant only treats the strongest signal from the sensors as its desired signal and ignores others. In the following this subsection, we introduce the channel model used and the channel capacity between sensor m and the plant in URLLC, respectively.

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[1]The proposed method in this paper can be extended to the scenario with multiple plants.

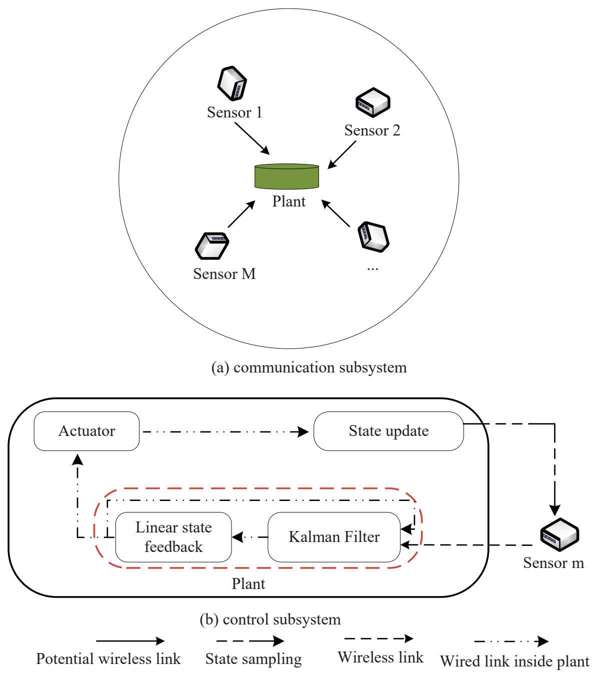

Fig. 1. Wireless communication sub-system.

1) Channel Model: We consider that the channel model consists of the small-scale fading and large-scale attenuation coefficients between sensor m and the plant, which are represented as h_m and g_m for the uplink from the m-th sensor to the plant, respectively. We assume that the large-scale attenuation coefficient is represented by path-loss, which can be expressed as [11]

$$g_m = \frac{C}{l_m^{\alpha}}, \tag{1}$$

where l_m is the distance between transceiver, C is a constant, and $\alpha \in [2, 6]$ is the path loss factor. Since we consider M sensors are uniformly distributed in a circle with the plant in the center, then we have the *probability distribution function* (PDF) of the sensors with distance l as

$$f_l(l) = \frac{2l}{R^2}, \tag{2}$$

where R is the radius of the circle. Then, we can obtain the pdf of the path loss as

$$f_{g_m}(g_m) = \frac{C g_m^{-2}}{R^2}, \quad g_m \geq \frac{C}{R^2}, \tag{3}$$

where $\alpha = 2$ is adopted [12].

The small-scale fading h_m follows Rayleigh distribution with mean zero and variance $\sigma_0^2 = 1$ [13]. Then, the PDF of its power can be expressed as

$$f_{h_m}(h_m) = e^{-h_m^2}, \tag{4}$$

However, since the end-to-end (E2E) latency is no more than 1 ms in URLLC, which is less than the channel coherence time [14]. Then, for the m-th sensor, the small-scale fading is constant during the transmission period [15].

2) Channel Capacity: According to [14] and [16], we can obtain the successful transmit bits in one frame for the m-th sensor in URLLC can be expressed as

$$R_m = C_m - \sqrt{\frac{V_m}{T_u B_m}} f_Q^{-1}(\varepsilon_m) + \frac{\log(T_u B_m)}{2 T_u B_m}, \tag{5}$$

where the first term on the right hand of (5) is the achievable Shannon capacity without transmission error, the second term is the minus error bits introduced by channel dispersion V_m, and the third term is the approximation of the reminder terms of order $\log(T_u B_m)/(T_u B_m)$. In addition, T_u is the allowed transmission latency and 1 ms is adopted in this paper, B_m is the occupied bandwidth, ε_m is the transmission error probability, and $f_Q^{-1}(\cdot)$ is inverse of Q function. Furthermore, we assume that the single-sided noise spectral density is represented by N_0, then according to [14], we have Shannon capacity C_m and channel dispersion V_m as follows, respectively,

$$C_m = T_u B_m \log\left(1 + \gamma_m\right), \tag{6}$$

and

$$V_m = T_u B_m (\log e)^2 \left(1 - \frac{1}{(1 + \gamma_m^2)}\right), \tag{7}$$

where γ_m is the received signal-to-noise-ratio (SNR) and can be expressed as

$$\gamma_m = \frac{h_m^2 B_m g_m P_m}{N_0 B_m} = \frac{h_m^2 g_m p_m}{N_0}, \tag{8}$$

where p_m is the single-sided transmission power of the m-th sensor.

B. Control

In this subsection, we provide the control model with communication time delay and reliability. As shown in Fig. 1 (b), the control process is conducted as follows. First, M sensors are activated with a certain probability to take samples of the current plant state and transmit them to the controller inside the plant. Then, the controller estimates the state by Kalman Filter based on the strongest signal among the sensors, calculates the control command, and sends it to the actuator by wired link. Finally, the plant state updates by the received control command. Based on the above control process, the linear differential equation of the plant can be expressed as [9]

$$d\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t)dt + \mathbf{B}\mathbf{u}(t)dt + d\mathbf{n}(t), \tag{9}$$

where $\mathbf{x}(t)$ is the plant state, $\mathbf{u}(t)$ is the control input, and $\mathbf{n}(t)$ is the disturbance caused by additive white gaussian noise (AWGN) with zero mean and variance $\mathbf{R}$. In addition, $\mathbf{A}$ and $\mathbf{B}$ represent the physical system parameter matrices (more details can be obtained in [17]).

We assume that s_n represents the sample period at time index n, which consists of the wireless transmission time delay T_u and an idle period $\bar{s}_n$. Their relationship can be expressed as

$$s_n = \bar{s}_n + T_u, \tag{10}$$

where $n = 1, 2, \cdots, N$ represents the sampling time index in the control process. Then, the discrete time control model with time delay $d_{m,n}$ can be obtained as [8]

$$\mathbf{x}_{n+1}=\mathbf{\Omega}_n\mathbf{x}_n+\mathbf{\Phi}_0^n\mathbf{u}_n+\mathbf{\Phi}_1^n\mathbf{u}_{n-1}+\mathbf{n}_n, \tag{11}$$

where $\mathbf{\Omega}_n = e^{\mathbf{A}s_n}$, $\mathbf{\Phi}_0^n = \left(\int_0^{\bar{s}_n} e^{\mathbf{A}t}dt\right) \cdot \mathbf{B}$, and $\mathbf{\Phi}_1^n = \left(\int_{\bar{s}_n}^{s_n} e^{\mathbf{A}t}dt\right) \cdot \mathbf{B}$.

Assuming $\xi_n = (\mathbf{x}_n^T \;\; \mathbf{u}_{n-1}^T)^T$ is the generalized state, then the control function in (11) can be rewritten as

$$\xi_{n+1} = \mathbf{\Omega}_d\xi_n + \mathbf{\Phi}_d\mathbf{u}_n + \bar{\mathbf{n}}_n, \tag{12}$$

where $\bar{\mathbf{n}}_n = (\mathbf{n}_n^T \;\; 0)^T$ and $\mathbf{\Phi}_d = \begin{pmatrix} \mathbf{\Phi}_0^n \\ \mathbf{I} \end{pmatrix}$. We assume $\mathbf{\Omega}_n = \mathbf{\Omega}$. Then, we have $\mathbf{\Omega}_d = \begin{pmatrix} \mathbf{\Omega} & \mathbf{\Phi}_1^n \\ 0 & 0 \end{pmatrix}$.

Considering the packet loss, we have the successful packet transmission probability $\Pr\{\alpha_n = 1\} = 1 - \varepsilon$ and the failed packet transmission probability $\Pr\{\alpha_n = 0\} = \varepsilon$, where ε represent that M sensors are failed in transmission. In addition, we assume that the state estimator is perfect. Then, we have the close-loop system in (12) can be rewritten as

$$\xi_{n+1} = \begin{cases} \mathbf{\Omega}_d\xi_n + \mathbf{\Phi}_d\mathbf{u}_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 1, \\ \mathbf{\Omega}_d\xi_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 0. \end{cases} \tag{13}$$

In the above discussion, we have obtained the wireless control model[2] where both communication time delay and packet loss have been taken into account. In the following of this paper, we will formulate the optimal problem and propose corresponding method to obtain D2D transmission scheme.

III. Optimal Problem Formulation

Our goal is to minimize power consumption under constraints of communication and control. In the following of this section, we formulate the optimal problem.

A. Objective Function

Since sensors are usually powered by battery [19], minimizing power consumption is very important in real-time wireless control systems. Thus, the objective is to minimize power consumption in this paper, which can be expressed as

$$J = \mathbb{E}\left[\sum_{m=1}^{M} p_{m,n}\right]. \tag{14}$$

B. Control Constraint

We consider the control state reduction rate as the control requirement to maintain control performance. e.g., control stability and control cost. To evaluate the effect of the control state reduction rate on the control performance, we adopt Lyapunov-like control cost function [2]

$$\Delta(\xi_n) = \xi_n^T\mathbf{Q}\xi_n, \tag{15}$$

[2]According to [18], to maintain the stability of the wireless control system, the following assumption should be satisfied: The packet loss probability in URLLC and the control system parameters satisfy $\rho\big((1-\varepsilon)(\mathbf{\Omega}_d+\mathbf{\Phi}_dK)\otimes(\mathbf{\Omega}_d+\mathbf{\Phi}_dK)+\varepsilon\mathbf{\Omega}_d\otimes\mathbf{\Omega}_d\big)$, where $\rho(\cdot)$ is the spectral radius, K is the control command feedback parameter, and $\otimes$ is the Kronecker product.

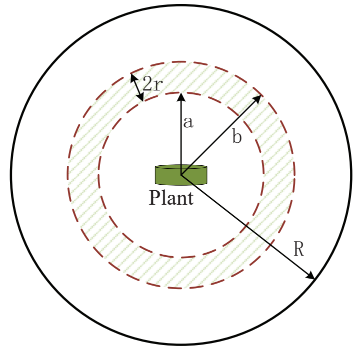

Fig. 2. The model to calculate the reliability probability.

where $\mathbf{Q}$ is positive definite. To guarantee the control stability, the Lyapunov-like function should decrease at given reduction rate[3] $\rho < 1$, which can also guarantee the state return to the pre-set point. Then, for any possible ξ_n, the Lyapunov-like functions needs to satisfy [20]

$$\mathbb{E}[\Delta(\xi_{n+1})|\xi_n] \leq \rho\Delta(\xi_n) + Tr(\mathbf{QR}'), \tag{16}$$

where $\mathbb{E}[\cdot]$ represents the expectation operator and $\mathbf{R}' = (\mathbf{R} \;\; 0)$.

C. Communication Constraint

The QoS requirements in URLLC include low latency and ultra-reliability. We assume that the latency is no more than the allowed upper bound in URLLC. Then, the communication constraint introduced by QoS requirement is the ultra-reliability, where we assume that the upper bound of the packet loss probability is ε_{th}. Here, the packet loss probability for the m-th sensor consists of two parts: the first part is the packet error probability ε_m in (5), and the second part is the packet drop probability when SNR γ_m is less than a threshold γ_{th} that can guarantee the received bits. To calculate the overall reliability probability inside the circle with radius R, we divide it into multiple circle rings. As shown in Fig. 2, we consider a typical circle ring with inside radius a, outside radius b and the length from the inside bound to outside bound $2r$. Then, the number of sensors inside the circle can be expressed as

$$M_a = \frac{b^2 - a^2}{R^2} \cdot M, \tag{17}$$

where we omit the subscribe m. Furthermore, we assume that the active probability is represented by $P_a(a)$ and the transmission power is represented by $p(a)$ when $r \to 0$. Then, we can obtain that the *cumulative distribution function* (CDF) of the SNR of the sensors inside the circle ring can be expressed as

$$\begin{aligned} F_\Gamma(\gamma|a \leq l \leq b) &= \Pr\left\{\frac{h^2gp(l)}{N_0} \leq \gamma\right\} \\ &= 1 - \frac{p(a)C}{N_0(b^2-a^2)\gamma}\left(e^{-\frac{\gamma a^2 N_0}{p(a)C}} - e^{-\frac{\gamma b^2 N_0}{p(a)C}}\right). \end{aligned} \tag{18}$$

[3]It is shown in [20] that the control convergence is guaranteed with $\rho < 1$.

Then, considering the SNR threshold γ_{th}, the packet drop probability inside the circle ring can be expressed as

$$F_\Gamma(\gamma_{th}|a\leq l\leq b)=1-\frac{p(a)C(e^{-\frac{\gamma_{th}a^2N_0}{p(a)C}}-e^{-\frac{\gamma_{th}b^2N_0}{p(a)C}})}{N_0(b^2-a^2)\gamma_{th}}. \quad (19)$$

For M_a sensors with active probability $P_a(a)$, we have the packet drop probability as

$$F_\Gamma(\gamma_{th}|a\leq l\leq b,M)=\left(F_\Gamma(\gamma_{th}|a\leq l\leq b)\right)^{M_aP_a(a)}. \quad (20)$$

Furthermore, we assume that the transmission error probability ε_m is constant for each sensor-to-plant link[4], which is represented as ε_0. Then, the CDF of the overall packet drop probability can be expressed as

$$F_\Gamma(\gamma_{th})=\int_0^R f_a(a)\left(F_\Gamma(\gamma_{th}|a\leq l\leq b,M)\right)\mathrm{d}a, \quad (21)$$

where $l\rightarrow 0$ and $f_a(a)=2a/R^2$. Then, the overall reliability probability for the plant can be expressed as

$$\Pr\{\alpha_n=1\}=1-\varepsilon_0-F_\Gamma(\gamma_{th}). \quad (22)$$

D. Problem Formulation

In this subsection, we formulate the optimal problem, which can be described in Problem 0, i.e., $\mathbf{P}_0$,

$$\begin{aligned}
\mathbf{P}_0:&\min_{P_a(a),p(a)}\quad J && (23a)\\
\text{s.t.}\quad &\mathbb{E}[\Delta(\xi_{n+1})|\xi_n]\leq\rho\Delta(\xi_n)+Tr(\mathbf{QR}'), && (23b)\\
&\Pr\{\alpha_n=1\}\geq 1-\varepsilon_{th}, && (23c)\\
&0\leq P_a(a)\leq 1, && (23d)\\
&0\leq p(a)\leq p_{\max}, && (23e)
\end{aligned}$$

where $J=M\int_0^R f_a(a)p(a)P_a(a)\mathrm{d}a$ based on the distance between the sensor and plant.

IV. Autonomous D2D Transmission Scheme

In this section, we will solve the optimal problem $\mathbf{P}_0$ to obtain D2D transmission activation and power allocation method. First, we analyze the relationship between communication and control, and convert the the control constraint in (23b) into the communication constraint based on the relationship. Then, we replace $\mathbf{P}_0$ with a regular communication optimal problem by the conversion. Finally, we develop an optimal algorithm by balancing reliability increase efficiency (RIE) for all transmit devices to obtain D2D transmission activation and power allocation method.

A. Relationship Between Control and Communication

From (13), we find that the expression $\mathbb{E}[\Delta(\xi_{n+1})|\xi_n]$ depends on the packet transmission probability, where we can obtain that the Lyapunov-like function can be expressed as

$$\begin{aligned}\mathbb{E}[\Delta(\xi_{n+1})|\xi_n]=&\Pr\{\alpha_n=1\}\xi_n^T\mathbf{\Omega}_{e_1}^T\mathbf{Q}\mathbf{\Omega}_{e_1}\xi_n\\&+\Pr\{\alpha_n=0\}\xi_n^T\mathbf{\Omega}_{e_0}^T\mathbf{Q}\mathbf{\Omega}_{e_0}\xi_n+Tr(\mathbf{QR}').\end{aligned} \quad (24)$$

[4]This assumption is reasonable when the modulation, channel coding, and other parameters related with transmission probability are identical.

Submitting (24) into (23b), we can obtain

$$\Pr\{\alpha_n=1\}\geq\frac{\xi_n^T(\mathbf{\Omega}_{e_0}^T\mathbf{Q}\mathbf{\Omega}_{e_0}-\rho\mathbf{Q})\xi_n}{\xi_n^T(\mathbf{\Omega}_{e_0}^T\mathbf{Q}\mathbf{\Omega}_{e_0}-\mathbf{\Omega}_{e_1}^T\mathbf{Q}\mathbf{\Omega}_{e_1})\xi_n}, \quad (25)$$

where $\xi_n\neq 0$. Let

$$c=\sup_{y\in\mathbb{R}^n,y\neq 0}\frac{y^T(\mathbf{\Omega}_{e_0}^T\mathbf{Q}\mathbf{\Omega}_{e_0}-\rho\mathbf{Q})y}{y^T(\mathbf{\Omega}_{e_0}^T\mathbf{Q}\mathbf{\Omega}_{e_0}-\mathbf{\Omega}_{e_1}^T\mathbf{Q}\mathbf{\Omega}_{e_1})y} \quad (26)$$

represent the supremum of the left-hand term in (25). According to [2], we can obtain the optimal c as c^*. Then, we can obtain that the communication reliability is not constrained by the requirement in URLLC, but the control reduction rate requirement from control systems, i.e., $c^*(\rho)$. Then, $\mathbf{P}_0$ can be rewrite as

$$\begin{aligned}
\mathbf{P}_1:&\min_{P_a(a),p(a)}\quad J && (27a)\\
\text{s.t.}\quad &F_\Gamma(\gamma_{th})\leq 1-\varepsilon_0-c^*,(23d),\ \text{and}\ (23e).
\end{aligned}$$

B. Optimal Sensor Activation and Power Allocation

In this subsection, we propose an optimal algorithm to solve the problem $\mathbf{P}_1$, where compared with traditional exhaustive search algorithm with exponential complexity, the complexity of our algorithm grows linearly.

1) Failed Reduction Efficiency: To obtain the optimal solution, we first introduce the FRE. The average power consumption can be expressed as

$$J_c(a)=P_a(a)p(a). \quad (28)$$

Then, the packet drop probability in (20) can be rewritten as

$$F_\Gamma(\gamma_{th}|a\leq l\leq b,M)=\left(F_\Gamma(\gamma_{th}|a\leq l\leq b)\right)^{M_a\frac{J_c(a)}{p(a)}}. \quad (29)$$

The FRE is defined as the ratio of the packet drop probability and the power consumption $J_c(a)$. Then, FRE can be obtained by taking partial derivation on $J_c(a)$ in (29), i.e.,

$$\begin{aligned}D\left(J_c(a),p(a),a\right)=&\frac{\partial F_\Gamma(\gamma_{th}|a\leq l\leq b,M)}{\partial J_c(a)}\\=&\frac{M_a}{p(a)}\ln\left(F_\Gamma(\gamma_{th}|a\leq l\leq b)\right)\left(F_\Gamma(\gamma_{th}|a\leq l\leq b)\right)^{M_a\frac{J_c(a)}{p(a)}},\end{aligned} \quad (30)$$

where the FRE is negative since $\ln\left(F_\Gamma(\gamma_{th}|a\leq l\leq b)\right)$ is negative. This means that lower FRE leads to larger power efficiency.

2) Transmission Power Simplification for FRE: Given average power $J_c(a_0)$ at a certain distance a_0, the FRE is a function of $p(a_0)$. Once the optimal $p(a)$ is obtained for all a and $J_c(a)$, i.e., $p^*(a)=f(a,J_c(a))$, the FRE is a function of $J_c(a)$ and a. Then, by $p^*(a)=f(a,J_c(a))$, the parameters to solve (27) change from three to two, where after we obtain optimal $J_c(a)$, $p^*(a)$ can be calculated. Next, we focus on obtaining the optimal $p^*(a)$ for given a and $J_c(a)$, which can be obtain by solving the following optimal problem,

$$\begin{aligned}
\mathbf{P}_2:&\min_{p(a)}\quad D\left(J_c(a),p(a),a\right) && (31a)\\
\text{s.t.}\quad &0\leq p(a)\leq p_{\max}. && (31b)
\end{aligned}$$

We need to note that solving $\mathbf{P}_2$ in (31) is equivalent to solve $\mathbf{P}_1$ in (27) for given a and $J_c(a)$. Taking partial derivation on $p(a)$ in (31a), we can obtain (32) on the top of next page, where $(F_\Gamma(\gamma_{th}|a \le l \le b))'$ is the partial derivation on $p(a)$.

Observing (32), it is difficult to solve (31) by the derivation. To solve the problem, we adopt exhaustive search method in [21] to obtain the optimal $p^*(a)$. The complexity of the method is determined by the length of quantized values of a and $J_c(a)$. We assume the length of quantized values of a and $J_c(a)$ is μ and ν, respectively. Then, the computing complexity is $\mu \times \nu$.

3) Optimal Solution: By obtaining $p^*(a) = f(a, J_c(a))$, the parameters to solve (27) change from three to two. Then, the FRE can be expressed as $D\left(J_c(a), p^*(a), a\right)$. To obtain the solution for (27), we can prove that the following property holds.

Property 1: *For each distance a, the FRE with $p^*(a)$ strictly increases with average power $J_c(a)$.*

This property indicates that larger power consumption at the sensor leads to lower power efficiency, where we can obtain the minimum FRE when $J_c(a) = 0$.

We can set a FRE threshold $\varphi < 0$ to determine the transmission power of the sensor, where the threshold holds for all sensors since the threshold φ is obtained by the distance a. Then, we can obtain $J_c(a)$ as the expression in (33) at the top of next page. Substituting (33) into (30), we can obtain the optimal $J_c^*(a)$ as the expression in (34) at the top of next page. Then, substituting (34) into (29), we can obtain the failed probability for distance a as

$$F_\Gamma(\gamma_{th}|a \le l \le b, M, \varphi) = \left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)^{M_a \frac{J_c^*(a)}{p^*(a)}}. \quad (35)$$

From (22) and (35), we can obtain the reliability as

$$\Pr{}^*\{\alpha_n = 1\} = 1 - \varepsilon_0 - \int_0^R f_a(a) F_\Gamma(\gamma_{th}|a \le l \le b, M, \varphi) \mathrm{d}a. \quad (36)$$

Let $\Pr^*\{\alpha_n = 1\} = c^*$. Then, we can obtain the optimal $J_c^*(a)$ for the sensors by finding suitable φ. Finally, the transmission power $p^*(a)$ for the sensor and the activate probability $P_a^*(a)$ can be obtained by solving $p^*(a) = f(a, J_c(a))$ and (28), respectively.

4) Computing Complexity: As the above discussion, the computing complexity is $\mu \times \nu$ by exhaustive search method to find $p^*(a) = f(a, J_c(a))$. If the computing complexity in finding optimal solution is θ. Then, the total computing complexity is $\eta = \theta \times \mu \times \nu$. Thus, the computing complexity of the proposed method is $\mathcal{O}(\eta)$ and increases linearly.

V. Simulation Results

In this section, we provide simulation results to demonstrate the performance of the proposed method, where the system models are the same as shown in Fig. 1. For URLLC, we assume that the bandwidth is 1 MHz, the single-sided noise spectral density is -174 dBm/Hz, the large-scale path loss constants is $C = -113.4$ dB, the radius of the circle is $R = 100$ m, the number of sensors is $M = 200$, the maximum transmission power for the sensors is -17 dBm, the transmission error probability is $\varepsilon_0 = 10^{-6}$, and the transmission time delay is $T_u = 0.5$ ms. In addition, the SNR thresholds are $[5 \quad 10 \quad 15]$ dB. For simplicity, we assume that control reduction rate requirement on communication reliability is $c^* = 99.999\%$. In addition, we consider a traditional D2D transmission method when not cellular assisted or traditional autonomous methods are not considered, where all the sensors are activated to guarantee the communication reliability requirement.

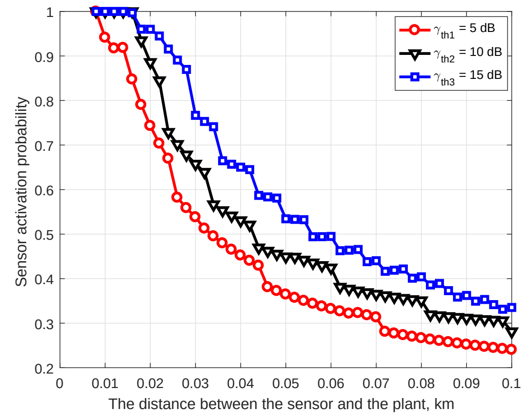

Fig. 3. The sensor activation probability with different distance between the sensor and the plant.

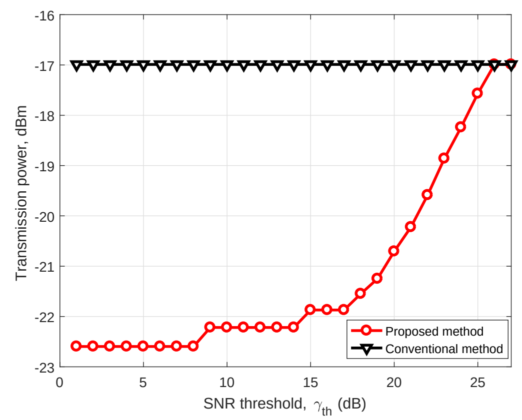

Fig. 4. The transmission power allocation with different SNR threshold γ_{th}.

Fig. 3 shows sensor activation probability when the distance between the sensor and the plant is different, where we considered different threshold γ_{th}. From the figure, all the curves with different SNR threshold decrease from 1 with distance increasing. This is reasonable since small distance between sensor and plant leads to high SNR with transmission power constraint, which can guarantee the SNR threshold with large probability. Considering different SNR thresholds γ_{th}, the curve with large γ_{th} is high than that with small γ_{th} when the distance between the sensor and the plant is fixed. This is reasonable since more active sensors are needed to satisfy larger γ_{th}. Thus, the activation probability is larger for larger γ_{th}. In addition, from the figure, compared with the traditional method with activation probability being 1, the proposed method in this paper do not need all the sensors keeping active.

Fig. 4 indicates the transmission power allocation when

$$D'\left(J_c(a), p(a), a\right) = \frac{\partial D\left(J_c(a), p(a), a\right)}{\partial p(a)} = \frac{M_a \left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)^{M_a \frac{J_c(a)}{p(a)}}}{p^3(a)\left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)} \ln\left(F_\Gamma(\gamma_{th}|a \le l \le b)\right) \cdot \tag{32}$$
$$\left[J_c(a) M_a \ln\left(F_\Gamma(\gamma_{th}|a \le l \le b)\right) + 1\right]\left[p(a)\left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)' - \left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)\ln\left(F_\Gamma(\gamma_{th}|a \le l \le b)\right)\right],$$

$$\begin{cases} J_c(a) = 0, & \text{if } D(0, p^*(a), a) > \varphi, \\ J_c(a) > 0 \text{ and } D(J_c(a), p^*(a), a) = \varphi, & \text{if } D(0, p^*(a), a) \le \varphi, \end{cases} \tag{33}$$

$$J_c^*(a) = \max\left(0, \frac{p^*(a)}{M_a} \cdot \frac{\ln\left(-\varphi p^*(a)\right) - \ln\left(-M_a \ln(F_\Gamma(\gamma_{th}|a \le l \le b)\right)}{\ln(F_\Gamma(\gamma_{th}|a \le l \le b))}\right). \tag{34}$$

SNR thresholds are different, where the distance between the sensor and the plant is 0.02 km. From the figure, the curve of the proposed method increases with SNR threshold γ_{th} increasing. This is reasonable since more transmission power at the sensor is needed to guarantee larger SNR threshold γ_{th}. However, the traditional method need to transmit with maximum available power to maintain larger SNR threshold γ_{th} with no information about the plant. In addition, from the figure, the proposed can reduce the power consumption by about 32% at most compared with the traditional method.

VI. Conclusions

In this paper, we proposed an autonomous D2D transmission method in URLLC for real-time wireless control systems, where both communication and control were jointly considered. In particular, we formulated an optimal problem to minimize transmission power consumption under constraints of URLLC and control. To solve the problem, we first analyzed the relationship between control and communication, where the control constraint was converted into the constraint on communication reliability. Then, we proposed a probability-based D2D activation method, where we set a threshold to determine the transmission strategy of the sensors. This allowed each sensor autonomously decide whether to participate the control process and significantly reduced the power consumption compared with traditional D2D transmission method.

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