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ERDT: Energy-Efficient Reliable Decision Transmission for Intelligent Cooperative Spectrum Sensing in Industrial IoT

RONGBO ZHU[1], (Member, IEEE), XUE ZHANG[1], XIAOZHU LIU[2,3], WANNENG SHU[1], TENGYUE MAO[1], AND BRIAN JALAIAN[3], (Member, IEEE)
[1]College of Computer Science, South-Central University for Nationalities, Wuhan 430074, China
[2]School of Automation, Wuhan University of Technology, Wuhan 430070, China
[3]Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Corresponding author: R. Zhu (rbzhu@mail.scuec.edu.cn)

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ABSTRACT Due to harsh environment, large number of sensors, limited energy, and spectrum scarcity, intelligent sensing becomes a key issue to enable many practical applications in industrial Internet of Things (IoT). In such an industrial environment with noise and interference, an efficient cooperative spectrum sensing (CSS) scheme can achieve spectrum sharing between primary users (PUs) and secondary users (SUs), and effectively solve the spectrum scarcity and reduce energy consumption to make the IoT smarter. As a vital part of CSS, decision transmission (DT) between SUs and fusion center (FC) plays a crucial role. In traditional DT, each SU will transmit its local decision to FC with orthogonal channel in each sensing, which does not consider the packet error and packet loss due to noise during transmission, and aggravates spectrum scarcity and energy consumption. An energy-efficient reliable DT (ERDT) scheme is proposed to enhance CSS in industrial IoT, which considers both packet error and packet loss. First, the CSS mathematical model based on DT is formulated. Second, with rigorous mathematical deduction, the correct decision probability and the energy consumption are analyzed for both ERDT and DT based on logic OR-rule and AND-rule under three cases, respectively: 1) bit error only; 2) packet loss only; and 3) both bit error and packet loss. Detailed simulation results show that, compared with DT, the proposed ERDT can increase correct decision probability and reduce energy consumption for CSS under three different cases. When the existence probability of PU is 50%, the energy consumption of ERDT is only half of that of DT in CSS. Furthermore, when there are 30 SUs in CSS, the existence probability of PU is 50%, both pocket loss rate and bit error rate are 0.05, and the correct decision probability of ERDT is approaching to 1 for CSS in industrial IoT.

INDEX TERMS Intelligent cooperative spectrum sensing, decision transmission, energy-efficient, industrial IoT.

I. INTRODUCTION

Internet of things (IoT) is a ubiquitous network fusing a variety of sensing technologies [1], [2], which provides the connection of sensors, actuators, RFID tags and other terminals, and has intelligent processing and smart control abilities to enable a large number of smart applications in the real world [3], [4], [33]. With a large number of sensors in self-organized way and the integration of advanced communication technologies, IoT can be used in many areas, such as intelligent transportation systems, intelligent manufacturing, food processing industry, environmental monitoring, security surveillance, and others industries [3], [4], which really will make the world smarter. Such applications lead to rapid expansion of the scale of industrial IoT [5], [6]. Meanwhile, massive data generated by different kinds of terminals increases the burden of packet transmission and spectrum resource in industrial IoT. Furthermore, harsh working environment, larger number of sensors will lead to energy consumption of power-limited sensors [7]–[9] and spectrum scarcity [10], [11], which will degrade the performance of industrial IoT greatly [12], [13].

Dynamic spectrum access with cognitive radio (CR) can effectively improve the spectrum efficiency and solve spectrum scarcity problem [12], which makes second users (SUs) opportunistically access the idle licensed spectrum of primary users (PUs) [10], [14], [15]. Hence, joining CR in IoT can meet the requirement of spectrum and improve spectrum utilization efficiently [13], [16]. Since CR networks become an important enabler for the development of future wireless infrastructures and many kinds of applications in the Internet [12], with considering the temporality characteristic of radio environment in transmission, the combined CR-based opportunistic networks and cognitive management system is proposed to achieve effective configuration in future Internet and IoT [13], [17]. Meanwhile, CR-based applications, such as location, spectrum sensing, public safety and disaster management, also make IoT more affordable and applicable in industrial areas [16].

As a key issue in CR, spectrum sensing plays a very important role in CR-based industrial IoT. However, single node spectrum sensing is unable to guarantee detection accuracy due to limited capacity, multipath fading, shelters in wireless environment and industrial applications. Cooperative spectrum sensing (CSS) scheme can effectively overcome the disadvantages of single node spectrum sensing with cooperation between nodes. However, additional energy will be consumed in local sensing, decision transmission (DT) and decision fusion in CSS.

In order to reduce energy consumption effectively, three aspects are considered in CSS: censoring, clustering and sensors selection. A double-threshold energy censoring method was proposed in DT phase [18], where only one bit decision (‘1’ or ‘0’) will be transmitted to fusion center (FC) for final decision whether PU exists or not, which reduces the transmission load and save energy greatly. Under the constraint of detection performance, a distributed spectrum sensing scheme was presented to reduce the number of sensors in DT to save energy consumption [19]–[21]. A repeated game model was adopted in CSS [12], where the participation number of sensors is treated as stimulation to promote sensors to participate in CSS, where the time of transmission decision is proportional to the participation number of sensors. However, the complexity of repeated game is very high.

Inspired by the clustering, a decision node (DN) is configured between SUs and FC to reduce energy consumption in DT [23]. All SUs transmit their local decision to DN instead of FC. Then DN makes the final decision and sends the result to FC. An event-driven CSS protocol was proposed in wireless cognitive sensor networks (WCSNs) [24]. Clustering will happen only when an event occurs, and automatically ends as the event ends. And the system will select appropriate sensors to participate in CSS based on the distance between the event and the sink.

To find the optimal threshold and eligible sensors performing sensing under the constraint of the lowest global detection probability and the highest global false alarm probability, an optimal CSS was proposed to minimize energy consumption [25]. However, with low signal-to-noise ratio (SNR), the proposed scheme will lead to high energy consumption. An energy-aware CSS model was proposed [26], which takes detection accuracy and energy awareness into account in sensors selection. The scheme firstly obtains the minimum number of sensors involving in sensing. Then the likelihood approach is used to select the appropriate sensors performing sensing. In [27], sensors selection and schedule optimization scheme was proposed to improve the energy efficiency, where sensors selection minimizes network energy consumption, and sensors schedule maximizes the lifetime of the network.

In order to improve the accuracy of cooperative sensing, there are two fusion methods in CSS: data fusion and decision fusion. Data fusion might bring better performance, however it also leads to more overhead and energy consumption. Meanwhile, decision fusion requires less overhead, and it is more suitable for energy-constrained sensors and terminals in IoT. Following this way, an improved DT is proposed in [28], which transmits all local decisions in the common channel to reduce energy consumption. However, it will lead to mutually interference in the common channel and affect final decision [29], [30]. An improved DT based on OR-rule was proposed in [31], where all SUs with local decisions ‘1’ transmit continuous signal to FC. And the power control algorithm was proposed to reduce interference among continuous signals.

Although there are many efficient DT schemes in CSS, several key issues should be addressed comprehensively in industrial IoT. Firstly, regardless of local decision of DT is ‘1’ or ‘0’, SU will transmit the decision to FC in each CSS, which leads to unnecessary energy cost greatly. In fact, according to logical OR-rule (AND-rule), FC only needs to know whether there is at least a local decision ‘1’ (‘0’) from SUs, and then it is able to make the final decision effectively. Secondly, most CSS schemes assume that the channel between SUs and FC is noise-free [32]–[34], which is far away from the harsh environment of industrial IoT, and may lead to fallacious decision. Furthermore, the existing schemes don’t consider the packet error and packet loss due to noise and transmission, which aggravate spectrum scarcity and energy consumption. Finally, some existing DT algorithms use the same channel to transmit continuous signal to FC, which is difficult to solve interference among sensors with limited energy and capacity.

This paper proposes an energy-efficient reliable decision transmission (ERDT) scheme for intelligent CSS in industrial IoT. The main contributions of the paper are summarized as follows:

1) CSS model based on ERDT is formulated, which considers both logical OR-rule and AND-rule.

2) ERDT considers both the packet error and packet loss due to noise interference and transmission in industrial IoT. Based on rigorous mathematical deduction, the correct decision probability and energy consumption are analyzed for both ERDT and DT under logical OR-rule and AND-rule in

three cases respectively: only bit error (noise interference), only packet loss (transmission error), and both bit error and packet loss (both cases).

3) ERDT improves correct decision probability in two aspects. On one hand, only SUs with decision ‘0’ (‘1’) will transmit local decisions to FC in OR-rule (AND-rule), which avoids the packet loss and interference, and also reduces energy consumption evidently. On the other hand, whatever decision FC receives, the decision will be considered as ‘0’ (‘1’) under OR-rule (AND-rule), which degrades negative influence of bit errors in transmission.

The rest of this paper is organized as follows. Section II presents the ERDT scheme, and correct decision probability and energy consumption are analyzed in detail. Section III validates the effectiveness of the proposed scheme by simulations. Finally, Section IV concludes the paper.

II. ENERGY-EFFICIENT RELIABLE DECISION TRANSMISSION

A. SYSTEM MODEL

In the system, there are N SUs and one FC, where each SU transmits local decision ‘0’ or ‘1’ to FC in one orthogonal channel, and transmission among SUs is independent. The system model is shown in Fig. 1. Let $S\left\{S_1 \ldots S_{N_1}\right\}$ denote N_1 SUs transmit decision ‘1’ to FC, $R\left\{R_1 \ldots R_{N_2}\right\}$ denote N_2 SUs send decision ‘0’ to FC, where N_1 and N_2 satisfy $N_1 + N_2 = N$. FC adopts a hard decision fusion rule, such as logical AND-rule or OR-rule, to make final decision on whether PU exists or not according to the received local decisions from SUs.

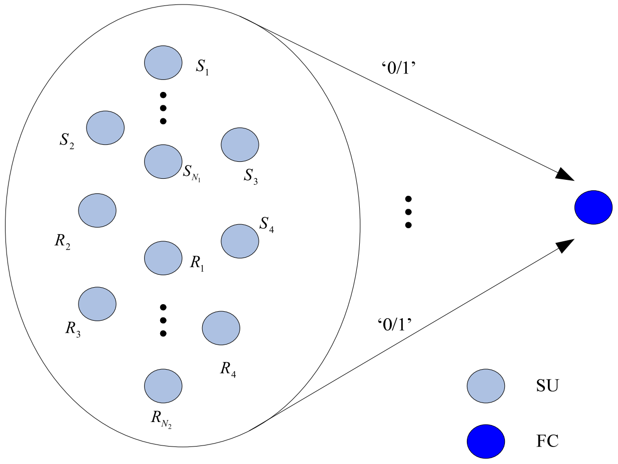

FIGURE 1. System model.

Definition 1 (OR-Rule of DT): For the system with NSUs in CSS, the SUs with local decision that PU exists will transmit ‘1’ to FC, and the SUs with local decision that PU is inexistent will transmit ‘0’ to FC; if FC receives any one decision ‘1’ from SUs, it will make final decision D that PU exists; otherwise PU is inexistent. The rule is given as:

$$D = \begin{cases} 1, & \textit{if } C\left(‘1’\right) \geq 1, \\ 0, & \textit{otherwise}, \end{cases} \tag{1}$$

where C(‘1’) denotes the number of decision ‘1’ that FC received from SUs. From the expression (1), we can see that regardless of the number of decision ‘1’ received from SUs is 1, 2, or N, FC will make the decision that PU exists.

Definition 2 (AND-Rule of DT): For the system with N SUs in CSS, the SUs with local decision that PU exists will transmit ‘1’ to FC, and the SUs with local decision that PU is inexistent will transmit ‘0’ to FC; if FC receives any one local decision ‘0’ from SUs, it will make final decision D that PU is inexistent. Otherwise, PU exists. The rule can be expressed as:

$$D = \begin{cases} 0, & \textit{if } C\left(‘0’\right) \geq 1, \\ 1, & \textit{otherwise}, \end{cases} \tag{2}$$

where C(‘0’) denotes the number of decision ‘0’ that FC received from SUs.

Unlike DT, for the proposed ERDT under OR-rule, only SUs with local decision ‘0’ will transmit the sensing result to FC, and SUs with local decision ‘1’ will not send their decisions to FC. The OR-rule fusion based on ERDT is shown in Fig. 2.

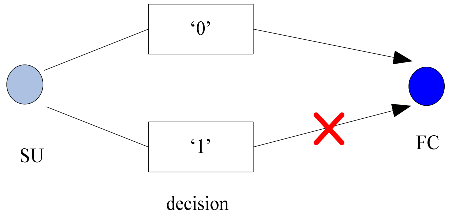

FIGURE 2. OR-rule fusion based on ERDT.

Definition 3 (OR-Rule of ERDT): In OR-rule of ERDT, if the number of local decisions ‘0’ and ‘1’ received from SUs is equal to the number of SUs participating in cooperation, FC will make the final decision D that PU is inexistent; otherwise PU exists. The rule can be expressed as:

$$D = \begin{cases} 0, & \textit{if } C\left(‘0’ \vee ‘1’\right) = N, \\ 1, & \textit{otherwise}. \end{cases} \tag{3}$$

where C(‘0’ $\vee$ ‘1’) denote the number of local decisions received from SUs.

According to definition 3, whatever decision FC receives, the decision will be considered as ‘0’ under OR-rule, which degrades negative influence of bit errors in transmission.

In AND-rule of ERDT, when SU detects PU in the system, it will transmit local decision ‘1’ to FC; otherwise, it will not send the decision ‘0’ to FC. The And-rule fusion based on ERDT is shown in Fig. 3.

Definition 4 (AND-Rule of ERDT): FC makes final decision D according to the number C(‘0’ $\vee$ ‘1’) of decision ‘1’ and ‘0’ received from SUs. If C(‘0’ $\vee$ ‘1’) is equal to the number of SUs, FC believes that PU exists; otherwise PU is inexistent. AND-rule of ERDT can be

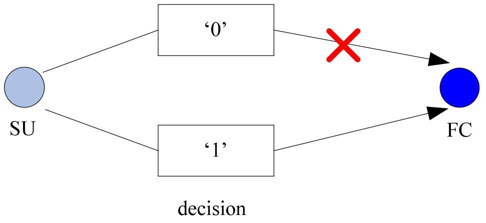

FIGURE 3. AND-rule fusion based on ERDT.

expressed as:

$$D = \begin{cases} 1, & if\ C\,(\text{`0'} \vee \text{`1'}) = N, \\ 0, & otherwise. \end{cases} \tag{4}$$

Similarly, in AND-rule of ERDT, FC will consider all received decisions as '1' to avoid bit errors in transmission.

B. CORRECT DECISION PROBABILITY

Correct decision includes two cases: absolute and relative correct decisions. The former assumes that FC will always successfully receive what SUs transmit. The latter considers there is error in transmission or packet loss of SU's decision. For example: there are 5 SUs in the system, SU_1, SU_2, SU_3, SU_4 and SU_5, which transmits decisions (1, 1, 0, 0, 1), respectively. In absolute correct decision, FC must receive the same decision set (1, 1, 0, 0, 1) without any error; While in relative correct decision, FC receives at least one decision '1', such as (0, 1, 1, 1, 0), or (1, 0, 0, 0), where the two kinds of sequences also are considered as the correct subset of decision under OR-rule of ERDT.

In absolute correct decision, there should not have any transmission error or packet loss. However, in practical industrial IoT, harsh environment and noise interference will lead to transmission errors or packet loss inevitably. Therefore, we only consider the relative correct decision of CSS in the following detailed analysis of two logical rules.

In order to analyze the correct decision probability clearly, ERDT considers both the packet error and packet loss due to noise interference and transmission in industrial IoT, and we consider three cases respectively: only bit error (noise interference), only packet loss (transmission error), and both bit error and packet loss (both cases).

1) BIT ERROR ONLY IN DATA TRANSMISSION

Let H_{00} denote the probability of SU transmitted decision '0' and FC received decision '0', H_{11} is the probability of SU transmitted decision '1' and FC received decision '1', H_{01} represents the probability of SU transmitted decision '0' but FC received decision '1' actually, and H_{10} denotes the probability of SU sent decision '1' but FC received decision '0' practically. Let p_1 be the bit error rate in data transmission. Since only considering the bit error in DT, it is assumed that the decision received by FC is either '0' or '1'. Then the probability of DT with bit error can be expressed as in Table 1.

TABLE 1. Probability of DT with bit error.

FC / SU	0	1
0	H_{00}	H_{01}
1	H_{10}	H_{11}

From Table 1, we can get the correct probability of DT is:

$$H_{00} = H_{11} = 1 - p_1, \tag{5}$$

and incorrect probability of DT is:

$$H_{01} = H_{10} = p_1. \tag{6}$$

Lemma 1 (Correct Decision Probability of DT): For the system with N SUs and one FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs send decision '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of DT under OR-rule is:

$$P_e = \begin{cases} 1 - \dfrac{N_1}{N} p_1^{N_1} - \dfrac{N_2}{N} (1 - p_1)^{N_2}, & if\ N_1 \geq 1 \\ (1 - p_1)^N, & otherwise. \end{cases} \tag{7}$$

Proof: According to definition 1, when $N_1 \geq 1$, FC should make final decision '1' (PU exists); when $N_1 = 0$, FC will make final decision '0' (PU is inexistent). In the following analysis, we will consider the above two cases.

Case I: $N_1 \geq 1$

In this case, in order to guarantee correction of the final decision, FC should receive at least one decision '1' from SUs, which includes the following two conditions:

i). When FC receives at least one decision '1' from SUs, FC makes correct decision that PU exists regardless of decision transmission in R is successfully or not. The correct decision probability P_{e_1} is:

$$P_{e_1} = P\,(C(\text{`1'}) \geq 1\,|N_1\,) = 1 - p_1^{N_1}. \tag{8}$$

ii). Similarly, if FC receives at least one decision '1' from R, it will also make correct decision. The correct decision probability P_{e_2} is:

$$P_{e_2} = P\,(C(\text{`1'}) \geq 1\,|N_2\,) = 1 - (1 - p_1)^{N_2}. \tag{9}$$

According to equations (8) and (9), the probability of correct decision of OR-rule in DT can be expressed as:

$$\begin{aligned} P_e &= P_{e_1} \cdot \frac{N_1}{N} + P_{e_2} \cdot \frac{N_2}{N} \\ &= 1 - \frac{N_1}{N} p_1^{N_1} - \frac{N_2}{N} (1 - p_1)^{N_2}. \end{aligned} \tag{10}$$

Case II: $N_1 = 0, N_2 = N$

In this case, all SUs in R must success to transmit decision to FC for ensuring correct decision, otherwise, FC would make fault decision. Hence, when PU is inexistent, the probability P_e of correct decision is:

$$P_e = H_{00}^{N_2} = (1 - p_1)^{N_2} = (1 - p_1)^N. \tag{11}$$

This completes the proof.

Lemma 2: For the system there are N SUs and one FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs transmit the decisions decision '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of DT under AND-rule is:

$$P_e = \begin{cases} 1 - \frac{N_1}{N}(1-p_1)^{N_1} - \frac{N_2}{N}p_1^{N_2}, & \textit{if } N_2 \geq 1 \\ (1-p_1)^N, & \textit{otherwise.} \end{cases} \quad (12)$$

Proof: According to definition 2, when all SUs in cooperation transmit decision '1' to FC successfully, FC will make the decision PU exists. Otherwise, PU is inexistent. In the following analysis, two cases are considered.

Case I: $N_2 \geq 1$

FC should receive at least one decision '0' from SUs. According to the difference of transmitters, two conditions are considered.

i). Firstly, SUs in S report decisions '0' to FC incorrectly. Secondly, decisions '0' (≥ 1) received by FC are transmitted by SUs in R. The probabilities P_{e_1} and P_{e_2} of correct decision of two conditions are expressed as follows:

$$P_{e_1} = P(C(\text{'0'}) \geq 1 \,|N_1) = 1 - P(H_{11})^{N_1} = 1 - (1-p_1)^{N_1}, \quad (13)$$

$$P_{e_2} = P(C(\text{'0'}) \geq 1 \,|N_2) = 1 - P(H_{01})^{N_2} = 1 - p_1^{N_2}. \quad (14)$$

With expressions (13) and (14), we can get the correct decision probability P_e of DT under AND-rule is:

$$\begin{aligned} P_e &= P_{e_1} \cdot \frac{N_1}{N} + P_{e_2} \cdot \frac{N_2}{N} \\ &= 1 - \frac{N_1}{N}(1-p_1)^{N_1} - \frac{N_2}{N}p_1^{N2}. \end{aligned} \quad (15)$$

Case II: $N_2 = 0, N_1 = N$

In this case, all SUs will send decision '1' to FC successfully, and FC should make final decision that PU exists. Hence, the correct decision probability P_e is:

$$P_e = H_{11}^{N_1} = (1-p_1)^{N_1} = (1-p_1)^N. \quad (16)$$

This completes the proof.

Lemma 3 (Correct Decision Probability of ERDT): For the system there are N SUs and one FC, there are N_1 SUs transmit decision '0' to FC. Let p_1 be the of bit error rate in data transmission, the correct decision probability P_e of ERDT under OR-rule is 1.

Proof: In ERDT, only SUs with decisions '0' will send their decisions to FC. Since there is only bit error in the system, whatever FC receives ('0' or '1'), the original decision data actually transmitted by SU is '0'. After t time slots, FC will determine whether PU exists or not according to the number M of decisions received by FC. When $N_1 \geq 1$, M must be less than N. And FC can correctly decide the existence of PU. When $N_1 = 0$, no matter what SUs transmit to FC, FC will treat them as decisions '0' and consider PU doesn't exist. Therefore, FC can correctly decide the status of PU with OR-rule in ERDT. Hence we can get the correct decision probability P_e is 1. ☐

Lemma 4: For the system with N SUs and one FC, there are N SUs transmit decision '1' to FC with bit error rate p_1 in transmission, the correct decision probability P_e of ERDT under AND-rule is 1.

Proof: According to definition 4, SUs with decision '1' will transmit their decisions to FC. Hence FC will consider all received the data is '1' when there is only bit error in the system. It can be seen that if $N_2 = 0$, the received decision number is equal to N, and FC can make right decision perfectly. Contrary, if $N_2 \geq 1$, the received decision number is smaller than N and FC can also rightly determine PU is inexistent. Similarly, regardless of whether channels are occupied or not, the probability P_e of correct decision of ERDT under AND-rule is 1. ☐

2) PACKET LOSS ONLY IN DATA TRANSMISSION

In this case, the transmission error is considered, and there isn't bit error caused by noise interference. Let T_{00} and T_{11} denote SUs transmit decision '0' and '1', and FC correctly receives them respectively, and T_{0X} and T_{1X} mean FC doesn't receive decision '0' and '1' successfully due to packet loss in transmission. The packet loss rate is p_2. Assumption transmission among SUs is independent. Then the probability of DT with packet loss is shown in Table 2.

TABLE 2. **Probability of DT with packet loss.**

FC / SU	Y	X
0	T_{00}	T_{0X}
1	T_{11}	T_{1X}

In Table 2, Y represents the successful transmission, and X denotes there is packet loss error. Then, we can get:

$$T_{00} = T_{11} = 1 - p_2, \quad (17)$$

$$T_{0X} = T_{1X} = p_2. \quad (18)$$

Lemma 5 (Correct Decision Probability of DT): For the system with N SUs and one FC, there are N_1 SUs send decision '1' to FC, and N_2 SUs send decision '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of DT under OR-rule with packet loss rate p_2 is:

$$P_e = \begin{cases} \frac{N_1}{N}(1 - p_2^{N_1}), & \textit{if } N_1 \geq 1 \\ (1-p_2)^N, & \textit{otherwise.} \end{cases} \quad (19)$$

Proof: In OR-rule of DT, SUs will transmit their decision '0' and '1' to FC. When $N_1 \geq 1$, FC makes the decision that PU exists; otherwise ($N_1 = 0$), PU is inexistent. The correct decision probability P_e is analyzed in the following two cases.

Case I: $N_1 \geq 1$

FC should receive at least one decision '1' from SU, namely there should be at least one SU transmitting decision successfully. Hence the correct decision probability P_e can be expressed as:

$$P_e = P(M_1 \geq 1 |N_1) \cdot \frac{N_1}{N} + P(M_1 \geq 1 |N_2) \cdot \frac{N_2}{N}$$
$$= \frac{N_1}{N}\left(1 - p_2^{N_1}\right), \tag{20}$$

where M_1 is the number of decision '1' received by FC.

Case II: $N_1 = 0, N_2 = N$

In this case, all SUs should transmit decisions '0' to FC successfully. Hence, we can get P_e:

$$P_e = T_{00}^{N_2} = (1 - p_2)^N. \tag{21}$$

This completes the proof.

Lemma 6: For the system with N SUs and one FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs send decisions '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of DT under AND-rule with packet loss rate p_2 is:

$$P_e = \begin{cases} \frac{N_2}{N}(1 - p_2^{N_2}), & \textit{if } N_1 \geq 1 \\ (1 - p_2)^N, & \textit{otherwise.} \end{cases} \tag{22}$$

Proof: When FC receives '1' from all SUs successfully, the decision of FC is that PU exists. Hence, the correct decision probability P_e is:

$$P_e = T_{11}^{N_1} = (1 - p_2)^N. \tag{23}$$

When $N_2 \geq 1$, at least one SU successfully transmit decision '0' to FC. The correct decision probability P_e is:

$$P_e = P(C(\text{`0'}) \geq 1 |N_1) \cdot \frac{N_1}{N} + P(C(\text{`0'}) \geq 1 |N_2) \cdot \frac{N_2}{N}$$
$$= \frac{N_2}{N}\left(1 - p_2^{N_2}\right). \tag{24}$$

This completes the proof.

Lemma 7 (Correct Decision Probability of ERDT): For the system with N SUs and one FC, there are N_1 SUs with decision '1', and N_2 SUs send decision '0' to FC, where N_1 and N_2 satisfy $N_1 + N_2 = N$, and the correct decision probability P_e of ERDT under OR-rule with packet loss rate p_2 is:

$$P_e = \begin{cases} 1, & \textit{if } N_1 \geq 1 \\ (1 - p_2)^N, & \textit{otherwise.} \end{cases} \tag{25}$$

Proof: According to definition 3, only SUs with decision '0' will transmit the decisions to FC in ERDT. FC makes final decision with comparing the number M of received decisions with N. And the SUs in S with decision '1' will not send their decisions to FC. Once S is not empty ($N_1 \geq 1$), M must be smaller than N, and then FC makes the final decision that PU exists, which means that the probability P_e of correct decision in ERDT is 1.

If S is empty ($N_1 = 0$), M is either smaller than N or equal to $N$where the former will lead to fault final decision of FC due to packet loss. The latter case indicates all SUs transmit their decisions successfully. Then the correct decision probability is $(1 - p_2)^N$. ☐

Lemma 8: For the system there are N SUs and one FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs with decision '0', where $N_1 + N_2 = N$, and the correct decision probability P_e of ERDT under AND-rule with packet loss rate p_2 is:

$$P_e = \begin{cases} 1, & N_2 \geq 1 \\ (1 - p_2)^N, & N_2 = 0. \end{cases} \tag{26}$$

Proof: In AND-rule of ERDT, only SUs with decision '1' in S will transmit their decisions to FC. Therefore, as long as R is not empty ($N_2 \geq 1$), FC makes correct decision since $M \leq N$, which indicates the P_e is 1.

When $N_2 = 0$, all SUs in S have to transmit decisions to FC successfully. Hence, the correct decision probability P_e of AND-rule in ERDT with packet loss ratio p_2 is $(1 - p_2)^N$. ☐

3) BOTH BIT ERROR AND PACKET LOSS IN DATA TRANSMISSION

In this case, we will consider there are bit error and packet loss simultaneously in data transmission. Let P_1 denote the decision probabilities received by FC from SUs in S, and P_2 is the decision probabilities received by FC from SUs in R. Assumption that transmissions among SUs is independent. Actually, each SU only sends one packet including one bit decision ('1' or '0') to FU. The following analysis considers there is only one bit error and one packet loss in each DT.

Lemma 9 (Correct Decision Probability of DT): For the system there are N SUs and a FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs send decision '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of DT under OR-rule with bit error ratio p_1 and packet loss ratio p_2 is:

$$P_e = \begin{cases} 1 - \frac{N_1}{N}(p_1 + p_2 - p_1p_2)^{N_1} \\ \qquad -\frac{N_2}{N}(1 - p_1 + p_1p_2)^{N_2}, & N_1 \geq 1, \\ (1 - p_1 - p_2 + p_1p_2)^N, & \textit{otherwise.} \end{cases} \tag{27}$$

Proof: According to definition 1, the following two cases are considered.

Case I: $N_1 \geq 1$

In order to make correct decision, FC should receive at least one decision '1' from SUs, where two cases are included.

i) FC receives at least one decision '1' from S without bit error and packet loss in transmission. Thereby, FC can make correct decision depending on getting at least decision '1' regardless of whether bit error and packet loss occur during transmission for SUs in R. In this case, the correct decision probability P_1 is:

$$P_1 = P(C(\text{`1'}) \geq 1 |N_1) = 1 - \sum_{i=0}^{N_1} C_{N_1}^i \cdot (p_1(1 - p_2))^i \cdot p_2^{N_1 - i}$$
$$= 1 - (p_1 + p_2 - p_1p_2)^{N_1}. \tag{28}$$

ii) Another case is SUs in R mistakenly transmit decision '1' to FC with bit error but without packet loss, which also makes FC do correct decision. And the probability P_2 of correct decision in this case is:

$$P_2 = P\left(C('1') \geq 1 \,|N_2\right) = 1 - \sum_{i=0}^{N_2} C_{N_2}^{i} \cdot \left((1-p_1)(1-p_2)\right)^{i} \cdot p_2^{N_2-i} = 1 - (1 - p_1 + p_1 p_2)^{N_2}. \quad (29)$$

Then, according to the expressions (28) and (29), we can get the probability P of correct decision of DT under OR-rule is:

$$\begin{aligned} P &= P_1 \cdot \frac{N_1}{N} + P_2 \cdot \frac{N_2}{N} \\ &= 1 - \frac{N_1}{N}(p_1 + p_2 - p_1 p_2)^{N_1} - \frac{N_2}{N}(1 - p_1 + p_1 p_2)^{N_2} \end{aligned} \quad (30)$$

Case II: $N_1 = 0, N_2 = N$

In this case, all SUs in cooperation should transmit decision '0' to FC successfully without bit error and packet loss. Hence, the correct decision ratio P is:

$$P = (H_{00}T_{00})^{N_2} = (1 - p_1 - p_2 + p_1 p_2)^{N}. \quad (31)$$

From expressions (30) and (31), we can get the correct decision probability P_e of OR-rule in DT with bit error ratio p_1 and packet loss ratio p_2 is the same as in expression (27). □

Lemma 10: For the system with N SUs and a FC, there are N_1 SUs transmit decision '1' to FC, and N_2 SUs send decision '0' to FC, where $N_1 + N_2 = N$. The correct decision probability P_e of DT under AND-rule with bit error rate p_1 and packet loss rate p_2 is:

$$P_e = \begin{cases} (1 - p_1 - p_2 + p_1 p_2)^{N}, & N_2 = 0, \\ 1 - \dfrac{N_1}{N}(1 - p_1 + p_1 p_2)^{N_1} & \\ \quad - \dfrac{N_2}{N}(p_1 + p_2 - p_1 p_2)^{N_2}, & N_2 \geq 1. \end{cases} \quad (32)$$

Proof: According to definition 2, considering the number of decision '0', if $N_2 \geq 1$, the PU does not exist; otherwise, PU exists.

The former case indicates SUs in R transmit at least one decision '0' successfully to FC or SUs in S transmit decision '1' to FC with bit error. Hence, we can calculate the correct decision probability P is:

$$\begin{aligned} P &= P\left(C('0') \geq 1 \,|N_1\right) \cdot \frac{N_1}{N} + P\left(C('0') \geq 1 \,|N_2\right) \cdot \frac{N_2}{N} \\ &= 1 - \frac{N1}{N}(1 - p_1 + p_1 p_2)^{N1} - \frac{N2}{N}(p_1 + p_2 - p_1 p_2)^{N2} \end{aligned} \quad (33)$$

The latter case indicates all SUs in S transmit decision '1' to FC successfully without bit error and packet loss. Hence the correct decision probability P is:

$$P = (H_{11}T_{11})^{N1} = (1 - p_1 - p_2 + p_1 p_2)^{N}. \quad (34)$$

This completes the proof.

Lemma 11 (Correct Decision Probability of ERDT): For the system with N SUs and a FC, there are N_1 SUs with decision '1', and N_2 SUs send decision '0' to FC, where $N_1 + N_2 = N$, and the correct decision probability P_e of ERDT under OR-rule with bit error rate p_1 and packet loss rate p_2 is the same as expression (25).

Proof: According to definition 3, only SUs with decision '0' will transmit their decisions to FC. And FC will evaluate the status of PU by comparing the number M of received decisions with N. When $N_1 \geq 1$, M is less than N and FC definitely decides that PU exists. Hence, we can get the correct decision probability P_e is 1.

When $N_1 = 0$, if M is equal to N, FC will consider PU does not exist, which requires that all decisions should be transmitted to FC successfully without packet loss. Hence the correct decision probability P_e of ERDT under OR-rule is $(1 - p_2)^N$. □

Lemma 12: For the system there are N SUs and a FC, N_1 SUs transmit decision '1' to FC, and N_2 SUs with decision '0', where $N_1 + N_2 = N$, and the correct decision probability P_e of ERDT under AND-rule with bit error rate p_1 and packet loss rate p_2 is the same as expression (26).

Proof: In AND-rule of ERDT, two cases are considered.

Case I: $N_2 \geq 1$, the number N of decision received by FC from SUs is less than N, and FC can definitely recognize that PU does not exist. Hence the correct decision probability P_e is 1.

Case II: $N_2 = 0$, every SU needs to successfully transmit the decision '1' to FC without packet loss; otherwise, FC can't make right decision. Hence the correct decision probability P_e is $(1 - p_2)^N$. □

C. ENERGY CONSUMPTION ANALYSIS

Let E be the total energy consumption of DT from SUs to FC in the system, C_{ti} denote the energy consumed by SU$_i$ in DT. E can be expressed as:

$$E = \sum_{i=1}^{N} C_{ti}, \quad (35)$$

where C_{ti} is proportional to the square of the distance between FC and the SU$_i$, and C_{ti} is:

$$C_{ti} = C_{t-elec} + e_{amp} d_i^2 \quad (36)$$

where C_{t-elec} represents energy consumption of SU transmitting one bit data to FC, e_{amp} is the amplifier gain, and d_i is the distance between FC and SU$_i$.

In the following analysis, we assume that the energy consumption C of each SU in DT is same.

1) ENERGY CONSUMPTION IN DT

According to the definitions of OR-rule and AND-rule in DT, regardless of decision is '0' or '1', SU will send it to FC. Therefore, every SU will consume same energy C to transmit the decision. The total energy consumption E of the system within t time slots, under OR and AND rules is:

$$E=\sum_{i=1}^{N_1}C+\sum_{i=1}^{N_2}C=NC. \tag{37}$$

2) ENERGY CONSUMPTION IN ERDT

In OR-rule of ERDT, if SU' decision is '1', it will not transmit decision to FC. And SUs with decision '0' will send the decisions to FC. On the contrary, in AND-rule, only SUs with decisions '1' will report their decisions to FC. Hence, we can get the total energy consumption E of ERDT under OR-rule and AND-rule is:

$$E=\begin{cases}\sum_{i=1}^{N_2}C=N_2C, & OR-rule\\ \sum_{i=1}^{N_1}C=N_1C. & AND-rule\end{cases} \tag{38}$$

III. SIMULATION RESULTS

In the industrial IoT system, assume that there are a FC node and multiple SUs nodes. And all SUs are uniformly distributed in a square field where FC is located in the center. If PU exists, the sensing decision of SUs is '1', otherwise the sensing decision is '0'. According to IEEE P802.22 [35], the global detection probability Q_d is 0.9 and the global alarm probability Q_f is 0.1. The energy consumption for each decision transmission is assumed to be 1. The following results are based on 1000 independent simulations.

A. CORRECT DECISION PROBABILITY

The correct decision probability P_e of DT and ERDT with varying bit error rate p_1 and the number N of SUs is shown in Fig. 4, where the existence probability p_{PU} of PU is fixed to 50%, and only consider the bit error in data transmission.

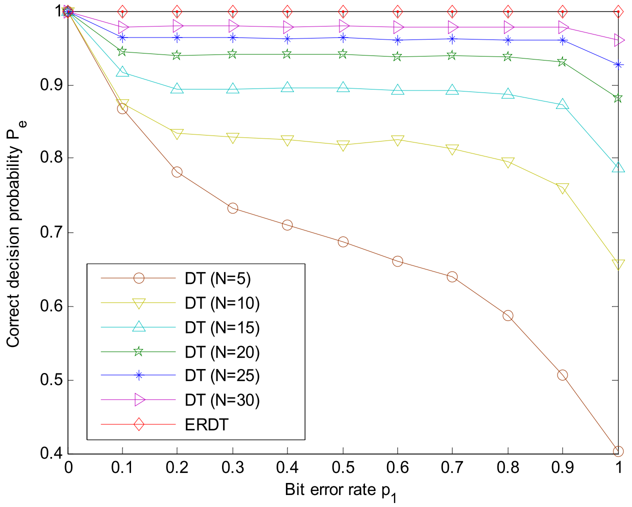

FIGURE 4. Correct decision probability P_e of ERDT and DT with varying bit error rate p_1 and the number N of SUs.

For DT, P_e will decrease with the increasing of p_1, and the smaller N, the faster P_e decreases. For example, when N =5, $p_1=0$, P_e is 1; when p_1 increases to 0.5, P_e reduces to 0.66; as p_1 increases to 1, P_e decreases to 0.4. When $N=10$, P_e is almost the same value as that at $p_1=0$. However, when p_1 increases to 1, P_e reduces to about 0.67, which is greater than that with $N=5$. Moreover, P_e will increase accordingly with the increasing of N, and gradually tends to 1. Such as, when $p_1=0.2$, P_e are 0.78, 0.85, 0.91, 0.94, 0.97 and 0.98 respectively ($N=5, 10, 15, 20, 25, 30$). The former is mainly due to the increasing of p_1, which reduces the probability of correct data transmission and leads to degrade the correct decision probability. The latter is because the increasing N indicates the number of nodes in CSS increases, which will improve the decision accuracy of CSS. When N is large enough, P_e tends to 1. While for ERDT, no matter what N and p_1, P_e is constant 1, which is not affected by varying N and p_1. The reason is that, the SUs with decision '1' will transmit data successfully to FC in ERDT, and as long as FC receives decision, which will be automatically considered the received decision as '0'. Such two methods increase the transmission accuracy of CSS and improve the decision accuracy. Hence, we can see that ERDT always outperforms DT in the terms of P_e when there only is bit error in the industrial IoT systems.

The correct decision probability P_e of DT and ERDT with varying packet loss rate p_2 and the number N of SUs is shown in Fig. 5, where the existence probability p_{PU} of PU is fixed to 50%, and only the packet loss is considered.

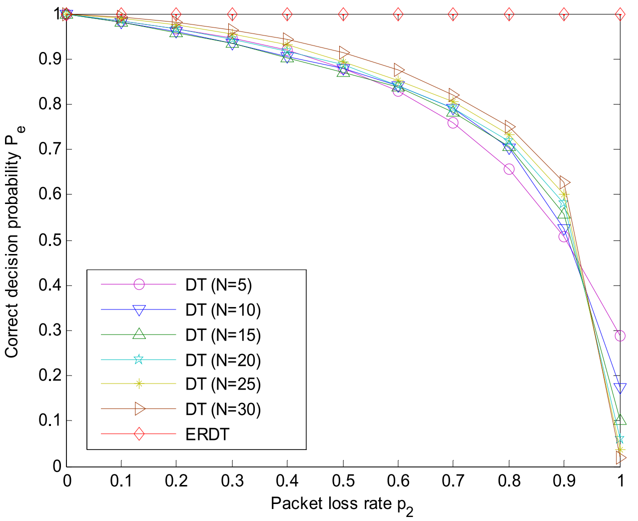

FIGURE 5. Correct decision probability P_e of ERDT and DT with varying packet loss rate p_2 and the number N of SUs.

As shown in Fig. 5, for DT, the curves of P_e appear convex decreasing as p_2 increases from 0 to 1 with different N. For instance, when $N=30$, $p_2=0$, P_e is 1; with p_2 increasing to 0.5, P_e reduces to 0.92; and when p_2 is 1, P_e tends to 0. When p_2 increases from 0 to 0.4, the number N of SUs has a less effect on P_e, and the values are 1, 0.99, 0.98, 0.96, and 0.94 ($p_2=0, 0.1, 0.2, 0.3, 0.4$). While p_2 increases from 0.4 to 0.9, N has a distinct influence on P_e. With the increasing of N, when $p_2 = 1$, P_e is 0.3, 0.16, 0.1, 0.07, 0.03, and 0.02 with $N = 5, 10, 15, 20, 25, 30$, respectively. It can be seen that N has little influence on P_e. The reason is that, when there is only packet loss error in the industrial IoT system, the decision accuracy is affected more by packet loss ratio p_2, according to the analysis of Lemmas 5 and 6.

The correct decision probabilities P_e of DT and ERDT with 10 SUs and 20 SUs are shown in Fig. 6 and Fig. 7 respectively, where the existence probability p_{PU} of PU is fixed to 50%, and bit error rate p_1 and packet loss rate p_2 vary from 0 to 1.

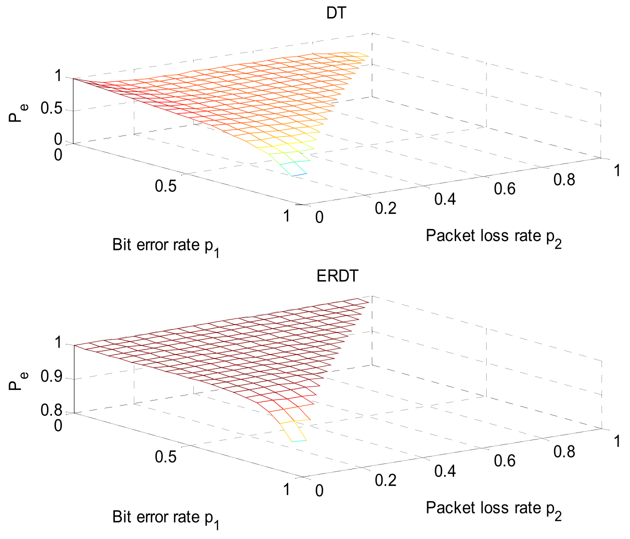

FIGURE 6. **Correct decision probability P_e of ERDT and DT with $N = 10$.**

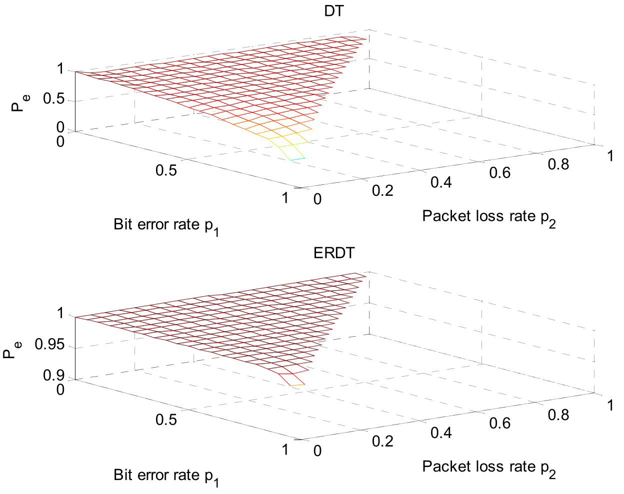

FIGURE 7. **Correct decision probability P_e of ERDT and DT with $N = 20$.**

As shown in Fig. 6, the correct decision probabilities P_e of DT and ERDT gradually decrease as p_1 and p_2 increase. While the P_e of ERDT always higher than that of DT. For DT, when p_1 and p_2 are both less than 0.05, P_e is 1; when p_1 and p_2 are greater than 0.75, P_e is less than 0.7; as p_2 increases to 1, P_e decreases to less than 0.2. For the proposed ERDT, when p_2 is less than 0.75, P_e always is 1; when p_2 is greater than 0.75, P_e is greater 0.8. For the special case $p_1 = 0$, P_e reduces from 1 to 0.49 in DT as p_1 increases from 0 to 1; while P_e remains constant 1 in ERDT under the same condition. The results show that the correct decision probability P_e of ERDT is higher than that of DT obviously.

The results in Fig. 7 show that, when the number N of SUs in cooperation increases to 20, the correct decision probability P_e of the proposed ERDT is always greater than 0.93. However in DT, when p_2 is greater than 0.55, P_e is less than 0.9; when p_2 increases from 0.95 to 1, P_e of DT decreases from 0.4 to less than 0.1. It is clear that P_e of ERDT is higher than that of DT. Furthermore, when p_2 is greater than 0.55, the correct decision performance of ERDT is much better than that of DT.

The results in Fig. 6 and Fig. 7 also show that the correct decision probability and stability of system are greatly improved with the proposed ERDT. And the more SUs in cooperation and the worse environment, the better performance of ERDT will achieve. The results also demonstrate the proposed ERDT is suitable for noise channel and interference environment to provide more reliable DT for CSS in industrial IoT.

B. ENERGY CONSUMPTION

1) BIT ERROR RATIO AND ENERGY CONSUMPTION

Since the energy consumption E is same for the cases with bit error, or with packet loss, or with both bit error and packet loss, the results in Fig. 8 and Fig. 9 show E of DT and ERDT with two fixed existence probabilities 50% and 60%, where p_1 increases from 0 to 1, and N varies from 5 to 15.

As shown in Fig. 8, when N is certain, the energy consumption E is constant with the increasing of p_1 in both ERDT and DT. The reason is that, in DT, regardless of what SU' decision is, energy will be consumed by SU to transmit decision to FC. Therefore, DT's energy consumption only is

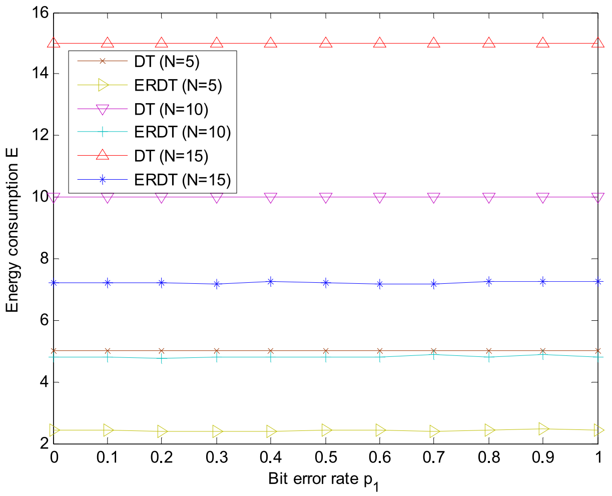

FIGURE 8. **Energy consumption of DT and ERDT with the existence probability 50%.**

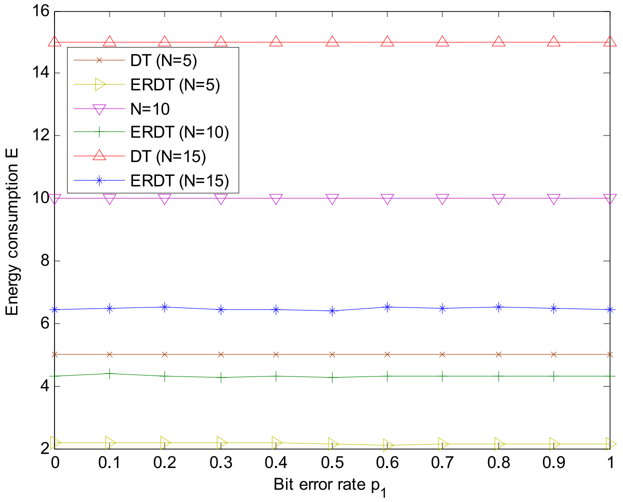

FIGURE 9. **Energy consumption under DT and ERDT with the existence probability 60%.**

proportional to the number N of SUs in cooperation. It is obvious that E is 5, 10, 15 respectively ($N = 5, 10, 15$) as p_1 varying from 0 to 1. In ERDT, energy consumption E is related to N_2, since only SUs with decision '0' will send their decisions to FC. Furthermore, the value of N_2 is related to p_{PU} and Q_d according to the expressions (36) and (38). When Q_d and p_{PU} both are fixed, the energy consumption E will keep constant too. The results in Fig. 8 show that, the larger N, the higher E. For ERDT, when N is 5, E is 2.4; as N increases to 10, E is 4.8; when N is 15, E increases to 7.2. However, it is observed that the energy consumption E of ERDT is less than that of DT, and is unrelated to bit error rate p_1. When p_{PU} is 50%, ERDT's energy consumption is only half of that of DT, which indicates the proposed ERDT can save energy consumption effectively and greatly.

The results in Fig. 9 show the existence probability p_{PU} of PU increasing to 60%. We can see the similar phenomena to both ERDT and DT. The reason is that the energy consumption E of DT is only related to N, and unrelated to p_{PU} and p_1. While in ERDT, the value of N_2 will decrease due to the increasing of p_{PU}, which also leads to the decreasing of energy consumption. It is easy to find that E is 2.01, 4.2, 6.2 respectively in ERDT, when N varies from 5 to 15 and p_1 increases from 0 to 1.

Compared the results in Fig. 8 with those in Fig. 9, it is obvious that energy consumption E of DT is not related to p_{PU}. While for the proposed ERDT, when p_{UP} increases from 50% to 60%, E decreases from 2.4 to 2.01 with $N = 5$, and when $N = 15$, E decreases from 7.2 to 5.6. The results show that the increasing of p_{PU} will have a positive impact on energy consumption of ERDT.

2) EXISTENCE PROBABILITY OF PU AND ENERGY CONSUMPTION

The energy consumption E of DT and ERDT under OR-rule and AND-rule with varying existence probability p_{PU} and N, is shown in Figs 10 and 11, respectively.

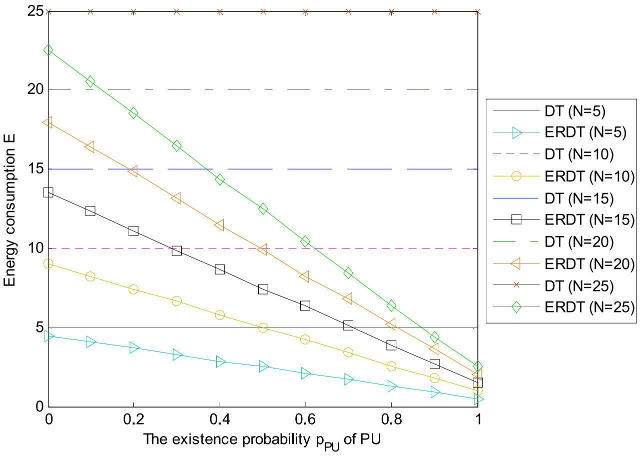

FIGURE 10. **Energy consumption of DT and ERDT under OR-rule with p_{PU}.**

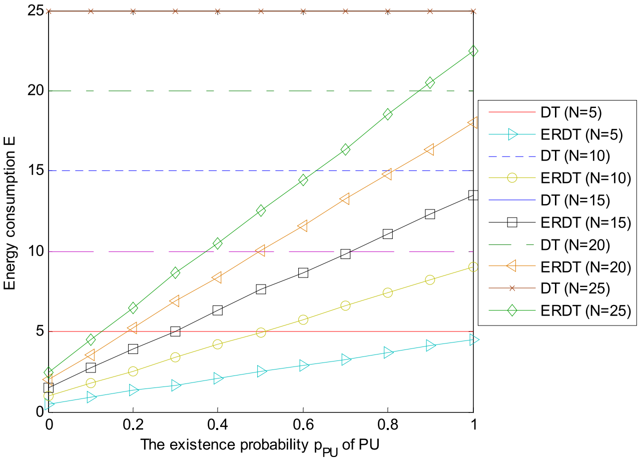

FIGURE 11. **Energy consumption of DT and ERDT under AND-rule with p_{PU}.**

In DT, no matter what decision of SU is, it will transmit the decision to FC. Therefore energy consumption of DT in CSS only is related to N. And it can be seen that the energy consumption E of DT always keep constant for the certain N in both Fig. 10 and Fig. 11, regardless of varying p_{PU}. As shown in Fig. 10, according to the definition of OR-rule in ERDT, only the SU with decision '1' will send its decision to FC. Hence, with the increasing of p_{PU}, the number of SUs transmitting decision '1' to FC will increase too, which will lead to the increasing of energy consumption. In ERDT, E tends to almost linear decreasing with the increasing of p_{PU}. When p_{PU} increases from 0 to 0.1, E decreases from 4.5 to 4 with $N = 5$, and from 13.5 to 12 with $N = 15$; when p_{PU} increases to 0.5, E reduces to 2.4, 5, 7.4, 10, 12 respectively with N changing from 5 to 25 with step 5. The results indicate the energy consumption decreases greatly with larger N as p_{PU} increases. Furthermore, for the same N, E of ERDT is lower than that of DT obviously. Another phenomena in Fig. 10, is that the greater p_{PU}, the less energy consumption. When PU doesn't exist, the energy consumption achieves its maximum value in ERDT, which indicates the proposed ERDT can implement CSS effectively to make full use of idle spectrum in industrial IoT.

As shown in Fig. 11, we can see the similar results under AND-rule. For the same N, the energy consumption E of ERDT is always less than that of DT. E of ERDT increases linearly as p_{PU} increases, while that of DT keeps constant. When p_{PU} is 0, E of ERDT are 0.6, 1, 1.5, 2 and 2.5, respectively; when p_{PU} increases to 1, E increases to 4.5, 9, 13.5, 18 and 22.5 respectively. With the increasing of p_{PU}, energy consumption of ERDT tends to linear increasing; however it is always less than that of DT. The results also show the proposed ERDT can save power efficiently in AND-rule with varying p_{PU} and N.

From Fig. 10 and Fig. 11, we can see that the energy consumption of DT is proportional to the number N of SUs in CSS. This is because, either AND-rule or OR-rule, regardless of what decision of SU is, it will transmit the decision to FC. While for ERDT, in OR-rule (AND-rule), only the SU with decision '0' ('1') will send the decision to FC. With the increasing of p_{PU}, the number of SUs with decision '0' will reduce. Therefore, the energy consumption of ERDT under OR-rule gradually reduces as p_{PU} increases; while the energy consumption of ERDT under AND-rule will increase with increasing of p_{PU}. Compared with DT, in OR-rule, the higher p_{PU}, the more energy ERDT saves; in AND-rule, the lower p_{PU}, the less energy ERDT consumes.

3) THE NUMBER OF SUs AND ENERGY CONSUMPTION

The energy consumption E of DT and ERDT under OR-rule and AND-rule is shown in Fig. 12 and Fig. 13 respectively, with varying p_{PU} and the number N of SUs in cooperation sensing.

The results in Fig. 12 show that, according to the definition of OR-rule, the energy consumption of DT only relates to N. Hence the energy consumption curves with different p_{PU} are same and proportional to N. And the energy consumption of ERDT increases linearly with N. When PU is inexistent, E is 4.5 with $N = 5$; E is 9 as N increases to 10; E increases from 36 to 40.1 with N increasing from 40 to 45. When p_{PU} increases to 0.5, E is 2.4 with $N = 5$; and E increases to 22.4 as N is 45. When N is 50, the energy consumption of ERDT is gradually decreased from 45 to 5 as p_{PU} increases from 0 to 1. Whatever p_{PU} is, the energy consumption of ERDT is obviously lower than that of DT, and the higher p_{PU}, the lower energy consumption in ERDT.

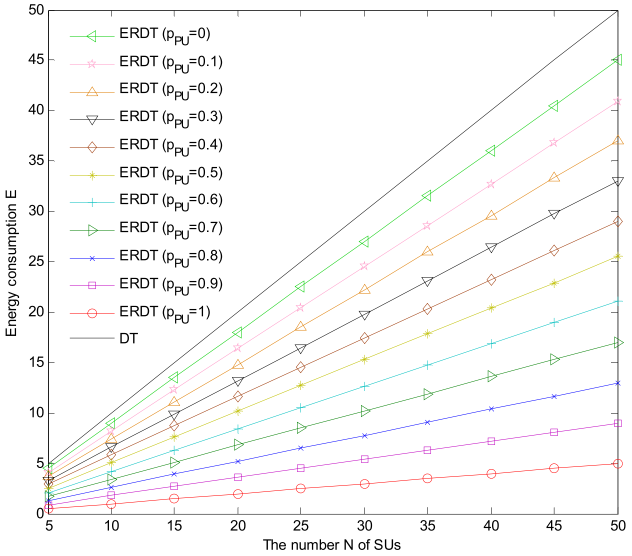

FIGURE 12. **Energy consumption of DT and ERDT under OR-rule with *N*.**

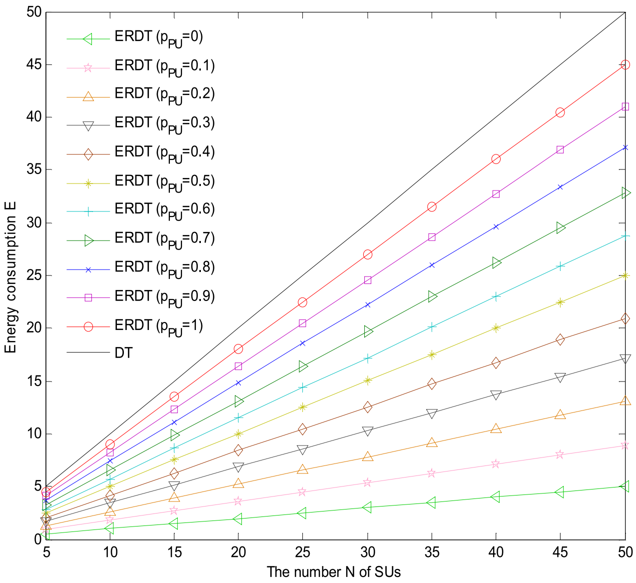

FIGURE 13. **Energy consumption of DT and ERDT under AND-rule with *N*.**

As shown in Fig. 13, we can see the similar results that the energy consumption E will increase linearly as N increases. However, the energy consumption of ERDT is less than that of DT in all cases. The results demonstrate that, compared with DT, ERDT can significantly reduce energy consumption, and the greater number N of SUs, the more energy saving. The higher p_{PU}, the more energy saving of ERDT is under OR-rule. And the smaller p_{PU}, the more energy saving of ERDT is under AND-rule. The results also show the proposed ERDT can degrade energy consumption with varying p_{PU} and the number N of SUs in cooperation sensing in industrial IoT.

IV. CONCLUSIONS

Reliable and energy-efficient CSS scheme is an important issue in industrial IoT with harsh environment, large number of power-limited sensors, and spectrum scarcity. A reliable and easily implemented CSS scheme called ERDT is proposed to reduce energy consumption and guarantee the decision correctness in CSS based on decreasing decision transmission. And the system model is formulated as the communication model between N SUs and a FC. The bit error and packet loss between SUs and FC are also considered to depict the packet error caused by noise interference and packet loss during transmission. Then, detailed analysis on correct decision probability, energy consumption of both DT and ERDT is presented with rigorous deduction in three cases. Detailed simulation results show that, compared with DT, the proposed ERDT can greatly reduce the energy consumption while ensuring the correct decision probability of CSS in industrial IoT, which is a simple, reliable and practical CSS scheme to make the industrial IoT smart to do correct decision in interference environment.

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RONGBO ZHU received the Ph.D. degree in communication and information systems from Shanghai Jiao Tong University, China, in 2006. He was a Visiting Scholar with the Virginia Polytechnic Institute and State University, Blacksburg, USA, from 2011 to 2012. He is currently a Professor with the College of Computer Science, South-Central University for Nationalities, China. His research interests include green networks, and performance optimization of wireless networks.

XUE ZHANG is currently pursuing the M.S. degree in computer science and technology with the College of Computer Science, South-Central University for Nationalities, China. Her research interests are in the areas of cognitive radio networks and power-efficient protocol design of computer networks.

XIAOZHU LIU received the Ph.D. degree in computer software and theory from Wuhan University, China, in 2011. She is currently an Associate Professor with the School of Automation, Wuhan University of Technology, China. She is also a Visiting Scholar with the Virginia Polytechnic Institute and State University, Blacksburg, USA. Her research interests are in the areas of mobile computing and data analysis.

WANNENG SHU received the Ph.D. degree from Wuhan University, China, in 2013. He is currently a Lecturer with the College of Computer Science, South-Central University for Nationalities, China. His research interests are mobile computing and computer networks.

TENGYUE MAO received the Ph.D. degree in communication and information systems from Wuhan University, China, in 2013. He is currently an Associate Professor with the College of Computer Science, South-Central University for Nationalities, China. His research interests are computer networks and protocol design of wireless networks.

BRIAN JALAIAN received the M.S. degrees in electrical engineering and operation research from the Virginia Polytechnic Institute and State University, in 2013 and 2014, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering with the Bradley Department of Electrical and Computer Engineering. His interests lie in the application of optimization and operation research in complex wireless communication system and network problems.

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