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Coded Redundant Message Transmission Schemes for Low-Power Wide Area IoT Applications

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***Abstract*—We propose a novel transmission scheme, suitable to IoT, which sends coded redundant information in independent packets. The results indicate that this scheme outperforms, in terms of reliability, transmit power, and coverage, the typical direct transmission strategy, schemes based on replications, and methods that embed coded redundant information in packets that contain new information. Moreover, we demonstrate the impact of selecting the most appropriate transmission scheme according to the target information outage probability and node location.**

***Index Terms*—Coded redundant message transmissions, energy efficiency, Internet of Things (IoT), LPWAN.**

I. Introduction

The Internet-of-Things (IoT) aims at providing connectivity for thousands of devices [1]. An IoT base station (BS) should cover many devices in a relatively simple manner, thus reducing infrastructure cost [2], [3]. Typically, the BS collects information from many devices [1]–[5], which transmit a small amount of data with short duty cycle. Ensuring energy efficient and reliable communications in resource constrained networks is a primary concern in IoT [1]. That is why Low Power Wide Area Networks (LPWANs), such as LoRa and SigFox, attract so much interest [2]. For instance, by using ultra narrow band (UNB) and low data rates, SigFox utilizes bandwidth efficiently and experiences low noise levels, resulting in high sensitivity and low power consumption [2].

Reliability is always a concern in wireless communications, and it can be increased by retransmission and redundancy schemes [3]–[6]. A feedback channel is usually employed to request retransmissions. However, LPWANs avoid the continuous use of the downlink channel, since this link is often near congested, as the BS covers several nodes at a low data rate [1]–[5]. So, as in [3]–[5], this possibility is not considered in this work. In contrast, redundancy-based schemes do not need any feedback information since the devices transmit redundant packets without prior request. Remarkable redundancy-based schemes are fountain codes [7], [8] and network coding [8], [9]. But since in LPWANs the one-hop link to the BS is essential to reduce energy consumption, solutions based on cooperative diversity [8] are typically not well suited [2]–[5].

Packet-level erasure coding on top of pure physical-layer coding is known to be beneficial in block fading channels [6]. In [3], by taking into account the randomness in time and frequency domains, a redundancy-based scheme using simple packet replications has been considered in a UNB based LPWAN. However, solutions based on coded packet redundancy [4], [5], [7] can bring increased reliability for the same rate. In [4], inspired by network coding, we proposed a non-cooperative transmission scheme based on coded redundant information, while in [5], a convolutional fountain erasure coding scheme for data recovery called DaRe is proposed.

In this letter, first we extend the scheme addressed in [4] to embed redundancy in more than just the next data packet and to include more than just one coded message per packet. Then, and more importantly, we propose a novel coded transmission scheme, which sends redundant information in new independent packets; unlike the aforesaid schemes [4], [5] which focus on the case where redundancy is embedded in the next data packets. Besides, we establish a fair comparison between the transmission schemes, imposing a maximum delay constraint, taking into account the impact of the protocol overhead, and ensuring the same channel time utilization.

The main contribution of this work is a novel transmission scheme, based on independent coded redundant information, that outperforms direct transmission, methods based on replications [3], and schemes based on embedded redundant messages [4], [5], in terms of reliability, transmit power, and coverage, while ensuring the same channel time utilization.

II. System Model

We consider the uplink between node $\mathcal{U}$ and the BS in an LPWAN. We assume additive white Gaussian noise channels subject to quasi-static Rayleigh fading in which the instantaneous signal-to-noise ratio (SNR) at the BS is $\gamma = \frac{gh^2 P_t}{N_o W}$, where P_t is the transmit power of node $\mathcal{U}$, N_o is the unilateral noise power spectral density, W is the channel bandwidth, h is the channel fading coefficient, independent and identically distributed (i.i.d.), where h^2 follows an exponential distribution with unit energy, $g = \mathcal{K}d^{-\alpha}$ is the path loss [10], where $\mathcal{K}$ is a frequency dependent constant, d is the distance between $\mathcal{U}$ and BS, and α is the path loss exponent.

The outage probability is the probability that a message from $\mathcal{U}$ is not recovered at the BS. A transmission fails whenever the instantaneous SNR is below a target SNR γ_{DT},

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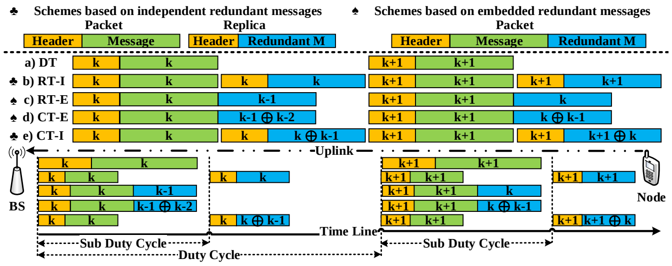

Fig. 1. Transmission schemes, for $n = 1$. The top scale is consistent with the binary length of the headers and messages, while the bottom scale is consistent with the temporal length.

required to guarantee reliable communication at a rate $\mathcal{R}_{\text{DT}}$. Then, the link outage probability between $\mathcal{U}$ and the BS is [10]

$$\mathcal{O}_{\text{DT}} = \Pr\left\{\gamma < \gamma_{\text{DT}}\right\} = 1 - e^{-\frac{N_0 W (2^{\mathcal{R}_{\text{DT}}/W} - 1)}{g P_t}}. \tag{1}$$

A. Direct Transmission

In the typical direct transmission (DT) scheme, each message is sent in a single packet with a header of size l_h and a payload of size l_m. The probability of information outage is associated with the loss of the packet conveying that information, and consequently to the link outage. As shown in Fig. 1-a, when the reception of the k^{th} transmitted packet fails, the k^{th} message is lost. Since each transmitted packet contains a single information message, then the information outage probability is simply $\mathcal{I}_{\text{DT}} = \mathcal{O}_{\text{DT}}$.

B. Replication Schemes

The simplest time diversity scheme uses repetition coding, sending replicas of the original message. This technique is referred here as Replication Transmission (RT). The replicas can be sent in new independent packets, which is referred here as Independent RT (RT-I), or embedded in the payload of the successive data packets, Embedded RT (RT-E). As in Fig. 1-b, with RT-I the k^{th} message can be contained in n successive independent replicas. Note that RT-I is the technique discussed in [3] and utilized by SigFox. In these scenarios, most of the applications have long time intervals between messages [1], [2], which allows the replicas to be sufficiently spaced in time to guarantee statistical independence. For the sake of fairness, considering the same channel time utilization according to DT, we assume the transmission rate to be a function of the number of replicas. Consequently, the rate of RT-I is [1]

$$\mathcal{R}_{\text{RT-I,n}} = (1+n)\mathcal{R}_{\text{DT}}. \tag{2}$$

Moreover, RT-E sends replicas embedded in the successive data packets that contain new information, which avoids the increase of protocol overhead at the expense of increasing the payload. As in Fig. 1-c, when RT-E with one replica is used the k^{th} message is contained in both the k^{th} and the $(k+1)^{th}$ data packets (note that the $(k+1)$ data packet also contains new information). Generalizing the idea, the k^{th} message could be embedded in the following n packets, increasing n times the payload size of the respective packets. Consequently, the transmission rate required by RT-E is

$$\mathcal{R}_{\text{RT-E,n}} = \left(1 + n\frac{l_m}{l_h + l_m}\right)\mathcal{R}_{\text{DT}}. \tag{3}$$

Note that, by adjusting the transmission rate we ensure the same channel time utilization by every scheme, even with different number of replicas, thus establishing a fair comparison.

Since both techniques have the same redundancy, n replicated messages, their information outage probabilities are

$$\mathcal{I}_{\text{RT-I,n}} = \mathcal{O}_{\text{RT-I,n}}^{(1+n)} \quad \text{and} \quad \mathcal{I}_{\text{RT-E,n}} = \mathcal{O}_{\text{RT-E,n}}^{(1+n)}, \tag{4}$$

so that, for each scheme, increasing the number of replicas has a beneficial impact in the exponent of the outage probability, but also a negative impact in the required transmit rate.

III. Coded Transmission Schemes

The schemes discussed in Section II are inefficient since we must double (RT-I) or almost double (RT-E) the transmission rate, compared to DT, to send a single replica. Thus, inspired by network coding and fountain codes, we propose the use of Coded Transmission (CT), in which successive replicas are combined before transmission, increasing the spectral efficiency. The use of linear combinations (e.g., XOR operation) of previous messages increases the redundancy with limited cost in terms of spectral efficiency. Just as in RT, the CT schemes can be of the independent (CT-I) and embedded (CT-E) types. Moreover, the transmission rates of CT-I and CT-E are obtained by evaluating (2) and (3), respectively.

A. Extending the Coded Transmission Scheme in [4]

Let $n = 1$, as in Fig. 1-d, so that the redundancy is embedded in the next data packet. Then, the k^{th} packet contains the original k^{th} message and a linear combination of the $(k-1)^{th}$ and $(k-2)^{th}$ messages. If the decoding of the k^{th} packet fails, then the k^{th} message can be obtained from the $(k-1)^{th}$ and $(k+1)^{th}$ or $(k+1)^{th}$ and $(k+2)^{th}$ or $(k+2)^{th}$ and $(k+3)^{th}$ packets. This example defines CT-E, which was introduced in [4], but the analysis ignored the effects of the protocol overhead and channel time fairness, while a formulation as a function of n was not presented.

If $n = 2$ is used, each message contains two linear combinations of the previous messages (in this case the k^{th} packet contains the original k^{th} message, a linear combination of the $(k-1)^{th}$ and $(k-2)^{th}$ messages, and a linear combination of the $(k-1)^{th}$ and $(k-3)^{th}$ messages) but, the number of independent packets is the same, while the required transmission rate increases. Thus, the required transmission rate of CT-E is the same as of RT-E. By enumerating [2] the events that lead to an outage for different values of n,

$$\mathcal{I}_{\text{CT-E,n}} = \mathcal{O}_{\text{CT-E,n}}^{3}\left(1 + \mathcal{O}_{\text{CT-E,n}}^{n-1} - \mathcal{O}_{\text{CT-E,n}}^{n} + \mathcal{O}_{\text{CT-E,n}}^{2n-2} - \mathcal{O}_{\text{CT-E,n}}^{2n-1}\right). \tag{5}$$

[1] $\mathcal{R}_{\text{X,n}}$ and $\mathcal{O}_{\text{X,n}}$ are the transmission rate and link outage probability when scheme X $\in$ {RT-I, RT-E, CT-E, CT-I} is used, with n redundant messages. $\mathcal{O}_{\text{X,n}}$ is written by replacing $\mathcal{R}_{\text{DT}}$ in (1) by $\mathcal{R}_{\text{X,n}}$ according to (2) or (3).

[2] To limit the decoding delay and the memory requirements, at most three redundant messages per information message are assumed, and so we only present the analysis between the $(k-3)^{th}$ and $(k+3)^{th}$ data packets. For instance, taking into account that SigFox messages are limited to 140 uplink messages per day [2], this limits the decoding delay to at most half an hour.

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Note that the diversity order is not increasing with n, making CT-E worse than RT-E, when $n \geq 2$. DaRe [5] is a similar embedded scheme, which uses linear combinations of previous messages, but performs better with higher window size values, limiting its application in scenarios with delay constraints[3].

B. Novel Independent Coded Transmission Scheme

Fig. 1-e illustrates the novel CT-I scheme with $n = 1$. The k^{th} message is sent in one independent data packet, but it is also contained in two additional packets: i) the coded message sent after the k^{th} data packet, in a linear combination of the $(k-1)^{th}$ and the k^{th} messages; ii) the coded message sent after the $(k+1)^{th}$ data packet, in a linear combination of the k^{th} and the $(k+1)^{th}$ messages. Table I lists the events (one per row), between the $(k-3)^{th}$ and $(k+3)^{th}$ data packets, that allow the k^{th} message decoding, according to the successful (S) or failed (F) decoding of that particular packet, where **M** and **R** are new message and coded redundant information, respectively. Thus, if the direct decoding of the k^{th} packet fails, the k^{th} message can still be obtained from the other events, which can be classified in two sets containing: i) the events that depend on the linear combination with the $(k-1)^{th}$ message, denoted as E_1 and highlighted in red; ii) the events that depend on the linear combination with the $(k+1)^{th}$ message, denoted as E_2 and highlighted in green. From Table I we can determine the probability of occurrence of both independent sets of events, which are $\mathcal{P}(E_1) = \mathcal{P}(E_2) = \mathcal{E}_1$,

$$\mathcal{E}_1 = (1-\mathcal{O}_{\text{CT-I,1}})^2 + \mathcal{O}_{\text{CT-I,1}}(1-\mathcal{O}_{\text{CT-I,1}})^3 + \mathcal{O}_{\text{CT-I,1}}^2(1-\mathcal{O}_{\text{CT-I,1}})^4. \quad (6)$$

Then, considering the union of the events in Table I, the information outage probability of CT-I with $n = 1$ is

$$\mathcal{I}_{\text{CT-I,1}} = 1 - \left[(1-\mathcal{O}_{\text{CT-I,1}}) + \mathcal{O}_{\text{CT-I,1}}\mathcal{P}\left(E_1 \bigcup E_2\right)\right] = \mathcal{O}_{\text{CT-I,1}} - \mathcal{O}_{\text{CT-I,1}}\left(2\mathcal{E}_1 - \mathcal{E}_1^2\right) = \mathcal{O}_{\text{CT-I,1}}^3 \mathcal{F}_1^2, \quad (7)$$

$$\mathcal{F}_1 = 1 + \mathcal{O}_{\text{CT-I,1}} + \mathcal{O}_{\text{CT-I,1}}^2 - 5\mathcal{O}_{\text{CT-I,1}}^3 + 4\mathcal{O}_{\text{CT-I,1}}^4 - \mathcal{O}_{\text{CT-I,1}}^5. \quad (8)$$

If $n = 2$ is used, the k^{th} message is sent in one independent data packet, but it is also contained in four additional packets, which leads to four independent sets of events that allow message decoding with probability of occurrence $\mathcal{E}_2$ and depending on: i) one coded message sent after the k^{th} data packet, in a linear combination of the $(k-2)^{th}$ and the k^{th} messages; ii) another coded message sent after the k^{th} data packet, in a linear combination of the $(k-1)^{th}$ and the k^{th} messages; iii) the coded message sent after the $(k+1)^{th}$ data packet, in a linear combination of the k^{th} and the $(k+1)^{th}$ messages; iv) the coded message sent after the $(k+2)^{th}$ data packet, in a linear combination of the k^{th} and the $(k+2)^{th}$ messages. Generalizing this idea, the number of complementary independent sets of events that allow decoding of the k^{th} message is $2n$ and $\mathcal{P}(E_j) = \mathcal{E}_{\text{n}} : \forall j \in \{1, 2, ..2n\}$. So, the information outage probability of CT-I can be formulated considering the union of these independent sets of events [11, Eq. 2.15], $\mathcal{I}_{\text{CT-I,n}} = 1 - \left[(1-\mathcal{O}_{\text{CT-I,n}}) + \mathcal{O}_{\text{CT-I,n}}\mathcal{P}\left(\bigcup_{j=1}^{2n} E_j\right)\right]$.

[3] DaRe [5] with a code rate equal to $1/2$ and $W = 2$ is equivalent to CT-E with $n = 1$, while if $W = 1$, then it is equivalent to RT-E with $n = 1$.

TABLE I
EVENTS FOR SUCCESSFUL DECODING OF CTI-I WITH $n = 1$

$k-3$		$k-2$		$k-1$		k		$k+1$		$k+2$		$k+3$	
M	**R**	**M**	**R**	**M**	**R**	**M**	**R**	**M**	**R**	**M**	**R**	**M**	**R**
						S							
				S		F	S						
						F		S	S				
		S		F	S	F	S						
						F		F	S	S	S		
S		F	S	F	S	F	S						
						F		F	S	F	S	S	S

TABLE II
SYSTEM PARAMETER VALUES

Parameter	Value	Ref.
Path loss constant, $\mathcal{K}$ (902 MHz carrier)	7.0×10^{-4}	[1], [2]
Channel bandwidth, W	100 Hz	[1], [2]
Transmission rate, $\mathcal{R}_{\text{DT}}$	100 bps	[1], [2]
Transmit power, P_t	14 dBm	[1], [2]
Distance to the BS, d	10 km	[1], [2]
Packet size of DT, $l_h + l_m$	12 Bytes	[1], [2]
Header length, l_h	4 Bytes	[12]
Payload length, l_m	8 Bytes	[12]
Path loss exponent, α	3	[4]
Target information outage probability, $\mathcal{I}_{\text{o}}$	10^{-3}	[4]
Noise power spectral density, N_{o}	-174 dBm/Hz	[4]

This union can be rewritten using the binomial function, and then by an algebraic approach based on the binomial theorem [11, Eq. 6.4] we determine a closed form expression for the information outage probability of CT-I as

$$\mathcal{I}_{\text{CT-I,n}} = \mathcal{O}_{\text{CT-I,n}} - \mathcal{O}_{\text{CT-I,n}}\sum_{j=1}^{2n}\binom{2n}{j}(-1)^{j+1}\mathcal{E}_{\text{n}}^j = \mathcal{O}_{\text{CT-I,n}} - \mathcal{O}_{\text{CT-I,n}}\left(1-(1-\mathcal{E}_{\text{n}})^{2n}\right) = \mathcal{O}_{\text{CT-I,n}}^{2n+1}\mathcal{F}_{\text{n}}^{2n}, \quad (9)$$

where

$$\mathcal{E}_{\text{n}} = (1-\mathcal{O}_{\text{CT-I,n}})^2 + \mathcal{O}_{\text{CT-I,n}}(1-\mathcal{O}_{\text{CT-I,n}})^3 + \mathcal{O}_{\text{CT-I,n}}^2(1-\mathcal{O}_{\text{CT-I,n}})^4, \quad (10)$$

$$\mathcal{F}_{\text{n}} = 1 + \mathcal{O}_{\text{CT-I,n}} + \mathcal{O}_{\text{CT-I,n}}^2 - 5\mathcal{O}_{\text{CT-I,n}}^3 + 4\mathcal{O}_{\text{CT-I,n}}^4 - \mathcal{O}_{\text{CT-I,n}}^5. \quad (11)$$

Note that, from (9) the diversity order of CT-I is $2n + 1$.

IV. NUMERICAL RESULTS

We evaluate the proposed schemes in terms of information outage probability, transmit power consumption, and coverage. All closed-form expressions were validated by Monte-Carlo simulations. Unless stated otherwise, we use the parameters in Table II, which coincide with those in the Sigfox standard [12]. Fig. 2 shows the information outage probability as a function of n, which is the number of replicas sent by RT or the number of coded messages sent by CT. Several interesting points arise: i) For all redundancy-based schemes, the optimum n depends on the communication distance, except for CT-E whose optimum value is $n^\star = 1$; ii) For the other schemes, the optimal value of n decreases as d increases, $n^\star = 3$ for RT-I and CT-I, as well as $n^\star = 5$ for RT-E when $d = 5$ km (see Fig. 2-a), while $n^\star = 2$ for RT-I and CT-I, as well as $n^\star = 3$ for RT-E when $d = 10$ km (see Fig. 2-b); iii) For the same d, $n^\star$ of RT-E is greater than $n^\star$ of RT-I and CT-I, due to the protocol efficiency of RT-E; iv) CT-I outperforms all other schemes in terms of information outage with $n^\star$.

Fig. 3-a shows the information outage probability as a function of the transmit power. Several interesting points arise: i) All redundancy-based schemes outperform DT, despite

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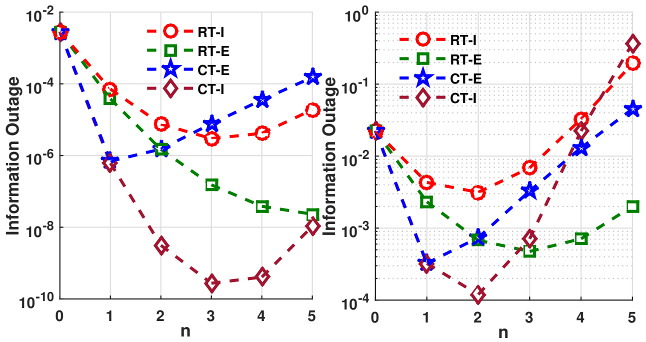

Fig. 2. Information outage as a function of the number of replicas or coded messages (n), for (a) $d = 5$ km and (b) $d = 10$ km.

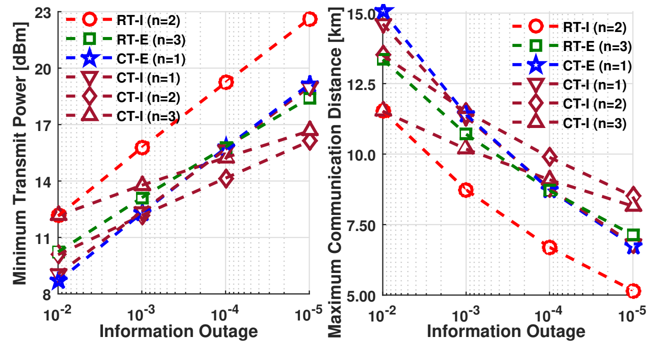

Fig. 4. (a) Minimum transmit power ($P_{t,\min}$) and (b) Maximum communication distance ($d_{\max}$) as a function of the information outage.

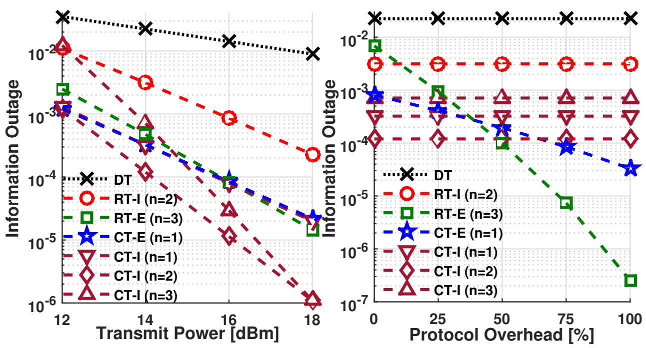

Fig. 3. Information outage as a function of (a) the transmit power (P_t) and (b) the protocol overhead.

being their respective link outage probabilities greater than $\mathcal{O}_{\text{DT}}$; ii) CT-I with $n^\star = 2$ outperforms all other schemes in terms of information outage, when 12 dBm $\leq P_t \leq$ 18 dBm; iii) The optimum n depends on P_t, for instance for CT-I if $P_t <$ 12 dBm then $n^\star = 1$, but if $P_t >$ 18 dBm then $n^\star = 3$. Fig. 3-b shows the information outage probability as a function of the protocol overhead, defined as the ratio between the header and the packet sizes. In this experiment, we set the DT packet size to 12 bytes, so the protocol overhead varies according to l_h and l_m (e.g., if $l_h = 4$ bytes, then $l_m = 8$ bytes and the protocol overhead is 33%). Two additional points: i) The performance of schemes based on embedded messages improves when the protocol overhead increases, due to (3); ii) CT-I with $n = 2$ outperforms all other schemes in terms of information outage, when the protocol overhead is less than 50 %, from which RT-E with $n = 3$ becomes the best option.

Fig. 4-a shows the minimum transmit power required to sustain a target information outage probability. The proposed scheme, CT-I with $n^\star = 2$ and $n = 1$, as well as CT-E with $n^\star = 1$, require half the transmit power of RT-I with $n^\star = 2$ to meet $\mathcal{I}_{\text{o}} = 10^{-3}$. Requiring less P_t to meet the same $\mathcal{I}_{\text{o}}$ and channel time utilization implies greater energy efficiency, since the additional computational cost of CT-I is minimal when compared to the RF power consumption and can thus be neglected. If information outage requirements are mild, then it is more convenient to use few replicas. Fig. 4-b shows the maximum range as a function of $\mathcal{I}_{\text{o}}$. For the case of a relatively large $\mathcal{I}_{\text{o}} = 10^{-2}$, CT-E with $n^\star = 1$ is the best option, while for more demanding target information outages, such as $\mathcal{I}_{\text{o}} \leq 10^{-3}$, CT-I with $n^\star = 2$ is the best option.

The results shown here vary quantitatively in real-world scenarios, but the performance metrics trends do remain. Besides note that, as seen in Fig. 1, when the original message transmission fails and the system must rely on a replica, RT-I decodes the k^{th} message within the k^{th} duty cycle, CT-I can decode the message within the same duty cycle or in the following duty cycles, but RT-E and CT-E always decode the message in the following duty cycles.

V. Conclusion

We proposed CT-I, which outperforms direct transmission, methods based on replications, and another coded transmission scheme based on embedded messages, in terms of reliability, transmit power, and coverage, with the same channel time utilization. CT-I transmits redundancy with less additional packets than the other schemes. The optimum number of redundant messages depends on range, protocol overhead, transmit power and information outage requirements.

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