An Alternative Non-cooperative Transmission Scheme based on Coded Redundant Information

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***Abstract*—Some of the future wireless networks are related to the provision of higher data rates and lower energy consumption. In contrast to the clear increasing spectrum demand, bandwidth is a limited resource. Cooperative diversity allows to increase the spectral efficiency and the reliability of the communication. However, in scenarios with high node density and high mobile data traffic volume the collaboration between multiple nodes can be a huge challenge. In this paper we focus on cognitive radio scenarios in which the users are only allowed to transmit with a limited power and have few opportunities to access the medium. Then, we propose an alternative non-cooperative transmission scheme based on coded redundant information through which users can automatically revert back, when cooperation is not possible. The results indicate that the proposed method outperforms direct transmission and simple repetition schemes, in terms of reliability, as well as spectral and energy efficiency.**

***Keywords*—Coded redundant information, energy efficiency, reliability, spectral efficiency, time diversity, transmission schemes.**

I. Introduction

The rapid increase in the usage of wireless technology and the pervasive wireless communication networks offer a range of individual and social benefits. Around 2020, the new 5G mobile networks should support multimedia applications with at least 1000-fold traffic volumes and 100 billion connected wireless devices [1]. Several challenges of future wireless networks cannot be met without providing higher data rates, reduced end-to-end latency, and lower energy consumption [2]. In contrast to the exponential growth of the wireless data traffic and the consequent increasing spectrum demand, bandwidth is a limited resource. Currently, most of the spectrum bands have been allocated, and studies have already shown that several of those spectrum bands are underutilized [3]. For example in [4], it was reported a spectrum occupancy about 32% from 20 MHz to 3 GHz for the indoor location of Germany. While in [5], the results showed a spectrum occupancy in Singapore as low as 4.54% in terms of used bandwidth, for the frequency range from 80 MHz to 5.85 GHz.

Fixed-spectrum utilization policies in wireless technologies have caused the spectrum shortage problem. Cognitive radio (CR) technology is a promising solution for the spectrum allocation problem, by dynamically assigning spectrum to secondary users (SUs) as long as the primary users (PUs) are not utilizing the licensed spectrum band [6]. Typically, if a PU transmits when a SU is utilizing its assigned spectrum band, the SU has to leave that spectrum band in order to avoid interference with that PU [7]. Nevertheless, the SUs may adopt diverse strategies to exploit radio spectrum dimensions (e.g. frequency, time, space, code, or angle) through different operation modes such as interweave, overlay, underlay, and hybrid [8]. In interweave mode, CR nodes can only use the radio spectrum if the channel is idle making spectrum sensing a critical step to prevent SUs from causing interference to PUs, which implies additional energy cost and processing complexity [9]. Overlay mode requires more sophisticated techniques from CR nodes to assist the primary communication while creating spectrum opportunities, by appropriately changing the characteristics of the PU signal [10]. While in underlay mode, SUs are allowed to transmit along with PUs simultaneously, as long as the interference caused by the SUs to the PUs do not exceed a predetermined threshold, which imposes stringent transmit power constraints. In order to avoid the high implementation complexity of the overlay mode, as well as the excessive consumption of time and energy related to spectrum sensing techniques, this paper focus on underlay mode.

Additionally, the increasing energy consumption by user and network devices represents a serious challenge. Even though the amount of energy used by each device is small, the massive deployment and widespread use makes the cumulative consumption considerable [11]. Then, for the near future, it is essential that the nodes can transmit more data with less energy consumption. The use of power allocation techniques to increase the energy efficiency in CR networks (CRNs), operating in underlay mode, has become a popular research topic in recent years [12], aiming at higher transmission rates [13] or lower outage probabilities [14] while minimizing the transmit power. In [13] it is investigated the performance of power control algorithms for rate and energy efficiency maximization in CRNs for line-of-sight conditions. However, the data transmission in wireless communications faces the issue of packet loss and link failure due to channel fading. Diversity techniques mitigate the effect of multipath fading and increase reliability by sending the same information through multiple independent paths so that the probability of successful transmission is higher [15]. Indeed, numerous forms of time diversity, frequency diversity, and spatial diversity are presents in modern wireless systems [16].

Cooperative diversity [17], [18] is a special class of spatial diversity techniques that is enabled by relaying [19], [20] and cooperative communications [21], [22]. Those techniques allow to transfer information from a source node to a destination node with the assistance intermediary nodes and are focused on increasing the spectral efficiency and the reliability. The application of these techniques in CRNs leads to the concept of cooperative CRNs, which have been an active research topic in recent years [23]. Additionally, the throughput of wireless networks can be further increased by using network coding (NC), in which intermediate nodes combine various incoming data packets from sender nodes and forward them in a single transmission [24]. In terms of link reliability and energy efficiency, power allocation can be used in a NC cooperative CRN in order to gain better performance than non-cooperative CRNs [14]. Recently, a tutorial has been published on NC cooperation [25], which discusses full benefits of NC in wireless networks, while [26] focus on providing a comprehensive survey on NC in CRNs.

However, a high mobile data traffic volume leads to channel congestion in scenarios with high node density, causing packet collisions and reliability loss. For this reason, some applications propose congestion control mechanisms, as to keep the channel load below a specified level to avoid congestion, for example in vehicular *ad hoc* networks (VANETs) [27]. In such scenarios the collaboration between multiple nodes can be a major challenge, since the relay retransmissions can also cause collisions. In [28] a lightweight piggybacking mechanism is proposed, which leverages only single-hop beacons data, in order to reduce channel contention and collisions. Besides, in [29] it is recognized that in Wireless Sensor Networks (WSNs) making cooperation practical involves several parameters that can significantly compromise its benefits. Therefore, it may be of great interest to have a high performing non-cooperative mode through which SUs can automatically revert back when cooperation is not the best choice.

In this paper we focus on scenarios in which the SUs are allowed to transmit with limited power and have few opportunities to access the medium, so collaboration between nodes or retransmission mechanisms may be not practically feasible. Then, we try to answer two questions for such scenarios:

- How to ensure communication reliability by direct transmission, without independent retransmissions?
- Is there an energy efficient and robust coding scheme for this scenario?

In this work we propose an alternative non-cooperative transmission scheme based on coded redundant information that outperforms direct transmission and simple repetition schemes, in terms of reliability, as well as spectral and energy efficiency.

The rest of this paper is organized as follows. Section II presents the system model, while in Section III a reliable transmission scheme based on time diversity and coded messages is described. In Section IV some numerical results are discussed, while Section V gives the conclusion and future work.

II. System Model

We consider a spectrum sharing scenario in which a cognitive radio *ad hoc* network operates at the edge of the primary coverage area and the analysis focuses on the primary downlink. Therefore, we neglect the impact of the primary base station on SUs, but the SUs should operate with limited transmit power $P_{\text{t,max}}$, to avoid interfering with PUs located near the boundaries. The system model is composed by two generic SUs ($\mathcal{U}_i$ and $\mathcal{U}_j$), which wish to communicate through direct transmission, when no relay is available for cooperation, but with high reliability and energy efficiency.

We assume additive white Gaussian noise channels subject to quasi static Rayleigh fading in which the signal-to-noise ratio (SNR) of the link between $\mathcal{U}_i$ and $\mathcal{U}_j$ is

$$\gamma_{ij} = \frac{g_{ij}|h_{ij}|^2 P_{\text{t}}}{N_0 W}, \tag{1}$$

where P_{t} is the transmit power, N_0 is the noise power spectral density, W is the channel bandwidth, g_{ij} is the average channel power gain and h_{ij} is the channel fading coefficient, independent and identically distributed (i.i.d.), whose squared envelop $|h_{ij}|^2$ follows an exponential distribution with unit energy, according to Rayleigh fading. Taking into account the effect of path loss, the average channel power gain is computed as [30]

$$g_{ij} = g_{\text{o}} \left(\frac{d_{\text{o}}}{d_{ij}} \right)^{\alpha}, \tag{2}$$

where d_{ij} is the distance between $\mathcal{U}_i$ and $\mathcal{U}_j$, d_{o} is a reference distance for the antenna far-field, α is the path loss exponent and g_{o} is the path loss constant which may depend on various system parameters such as antenna height and gain, cable losses and type of propagation environment. For the sake of simplicity, we consider that the value of g_{o} can be estimated by evaluating the free space path loss at distance d_{o}, this is

$$g_{\text{o}} = \left(\frac{\lambda_{\text{c}}}{4\pi d_{\text{o}}} \right)^2, \tag{3}$$

where $\lambda_{\text{c}} = c/f_{\text{c}}$ is the wavelength, $c = 3 \cdot 10^8$ m/s is the light speed and f_{c} is the carrier frequency.

Then, the outage probability $\mathcal{O}_{ij}$, is defined as the probability that a transmitted message from $\mathcal{U}_i$ could not be recovery at $\mathcal{U}_{\text{j}}$. We assume that a transmission between any two nodes fails whenever the instantaneous SNR of the link is below a predefined target SNR γ_{o}, required to guarantee a minimum transmission rate $\mathcal{R}_{\text{o}}$. Then, the link outage probability between $\mathcal{U}_i$ and $\mathcal{U}_j$ is computed as [30]

$$\mathcal{O}_{ij} = \Pr\left\{ \frac{g_{ij}|h_{ij}|^2 P_{\text{t}}}{N_0 W} < \gamma_{\text{o}} \right\} = 1 - e^{-\gamma_{\text{o}}/\bar{\gamma}_{ij}}, \tag{4}$$

where $\bar{\gamma}_{ij} = g_{ij}P_{\text{t}}/(N_0W)$ is the average SNR of the link and the target SNR can be estimated as $\gamma_{\text{o}} = 2^{\mathcal{R}_{\text{o}}/W} - 1$. Then, the outage probability of the link is computed as

$$\mathcal{O}_{ij} = 1 - \exp\left(-\frac{N_0W(2^{\mathcal{R}_{\text{o}}/W} - 1)}{g_{ij}P_{\text{t}}}\right), \tag{5}$$

and consequently the minimum transmit power required to meet a target information outage probability $\mathcal{I}_{\text{o}}$ is

$$P_{\text{t,min}} = -\frac{N_0W(2^{\mathcal{R}_{\text{o}}/W} - 1)}{g_{ij}\ln(1 - \mathcal{I}_{\text{o}})}, \tag{6}$$

subject to, $P_{\text{t,min}} < P_{\text{t,max}}$. The maximum transmission rate that SUs could achieve is given by

$$\mathcal{R}_{\text{max}} = W\log_2\left(1 - \frac{P_{\text{t,max}}g_{ij}\ln(1 - \mathcal{I}_{\text{o}})}{N_0W}\right). \tag{7}$$

III. Reliable Transmission Schemes

In the classical direct transmission scheme (CDTS), the probability of information outage is associated with the loss of the corresponding packets and consequently to the link outage. As shown in Fig. 1, when the reception of the k-th data packet fails, the k-th message is lost.

Since each transmitted packet contains a single message, then the information outage probability when CDTS is used is

$$\mathcal{I}_{\text{CDTS}} = \mathcal{O}_{ij}. \tag{8}$$

Typically, message losses are handled by retransmissions, but when the retransmission and cooperation are not possible, alternative mechanisms must be implemented.

A. Redundant Messages Transmission Scheme

The simplest time diversity schemes uses repetition coding. As shown in Fig. 1, when the time diversity is exploited by sending redundant information, the k-th message is contained in the k-th and $(k+1)$-th data packets. Then, the k-th message is lost only if the reception of both packets fails. This technique is referred here as Redundant Messages Transmission Scheme (RMTS) and its information outage probability is

$$\mathcal{I}_{\text{RMTS}} = \mathcal{O}_{ij}^2. \tag{9}$$

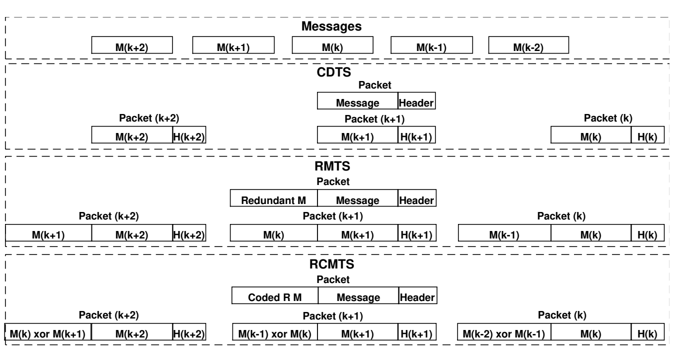

Fig. 1. Transmission Schemes

B. Redundant Coded Messages Transmission Scheme

However, the previous scheme is inefficient since it is necessary to double the size of the payload to create a simple redundancy. Based on coding we propose a transmission scheme, which achieves more redundancy with the same payload size of RMTS. In the Redundant Coded Messages Transmission Scheme (RCMTS) the k-th packet contains the original k-th message and a linear combination (e.g. XOR operation) of the $(k-1)$-th and $(k-2)$-th messages, see Fig. 1. Note that if the reception of the k-th packet fails the k-th message can still be obtained from the packets ($(k-1)$-th and $(k+1)$-th) or ($(k+1)$-th and $(k+2)$-th) or ($(k+2)$-th and $(k+3)$-th). Table I shows all the events that cause the k-th message outage, according to the successful (S) or failed (F) decoding of the packets involved. Then, the information outage probability of RCMTS is computed as the union of exclusive events

$$\begin{aligned}\mathcal{I}_{\text{RCMTS}} &= \mathcal{O}_{ij}^5 + 4\mathcal{O}_{ij}^4(1 - \mathcal{O}_{ij}) + 3\mathcal{O}_{ij}^3(1 - \mathcal{O}_{ij})^2 \\ &= 3\mathcal{O}_{ij}^3 - 2\mathcal{O}_{ij}^4 \approx 3\mathcal{O}_{ij}^3. \end{aligned} \tag{10}$$

C. Energy Efficiency

Since reliability is achieved by increasing the payload length, it is necessary to consider a performance metric that includes this cost. The size of the packets exchanged by the SUs depends on the transmission scheme used and let us denoted by L_{sch}, where sch $\in$ {CDTS, RMTS, RCMTS} and each packet consist of a packet header and payload, . Then, the communication energy efficiency, with unit given by messages per Joule, is [13]

$$EE_{\text{sch}} = (1 - \mathcal{I}_{sch})\left(P_{\text{t,sch}}\frac{L_{\text{sch}}}{\mathcal{R}_{\text{sch}}}\right)^{-1}. \tag{11}$$

IV. Numerical Results

In this section we discuss analytical and simulated results, in order to evaluate the performance of the proposed RCMTS scheme in terms of outage probability, as well as spectral and energy efficiency. All computer simulations were carried out using the Monte-Carlo method and Matlab. Unless otherwise specified we use the parameter values listed in Table II. It should be noted that the use of redundancy involves doubling the size of the payload, so assuming the header length equal to zero represents the worst case for these schemes, in comparative terms.

TABLE I. k-th Message Outage Events

Packets				
$(k-1)$	k	$(k+1)$	$(k+2)$	$(k+3)$
F	F	F	F	F
S	F	F	F	F
F	F	S	F	F
F	F	F	S	F
F	F	F	F	S
S	F	F	S	F
S	F	F	F	S
F	F	S	F	S

TABLE II. SYSTEM PARAMETER VALUES

Parameter	Value
Carrier frequency, f_c	5.89 GHz
Channel bandwidth, W	10 MHz
Distance between users, d_{ij}	50 m
Reference distance, d_o	1 m
Noise power spectral density, N_0	-174 dBm/Hz
Path loss exponent, α	3
Payload length	50 Bytes
Header length	0 Bytes
Target information outage probability, $\mathcal{I}_o$	10^{-3}
Transmit power, P_t	20 dBm

A. *Analysis of the information outage*

Fig. 2 shows the information outage probability as a function of the transmit power of the SUs, where it is clear that the simulated and analytical results match perfectly, according to (9) and (10). As expected, in all schemes the information outage probability decreases as P_t increases. This behavior is more accentuated in the RCMTS scheme, especially at high SNR regime. Additionally, it should be noted that the benefits of time diversity are present even when the transmission rate is doubled, for high transmit power. Note that, the information outage probability of RCMTS ($\mathcal{R}_o/W = 4$ bps/Hz) is even lower than the probability of RMTS ($\mathcal{R}_o/W = 2$ bps/Hz), for $P_t > 25$ dBm. However, when the transmission rate of RMTS and RCMTS is twice than that of CDTS, the use of low transmit power implies high outage probability, consequently the performance of RMTS (for $P_t \leq 12$ dBm) and RCMTS (for $P_t \leq 10$ dBm) becomes worse than that of CDTS. Note that these results can only be achieved when $P_{t,max} > P_t$. If $P_{t,max} = 20$ dBm the minimum information outage probability achieved by each scheme is limited to that achieved for $P_t = 20$ dBm (e.g. 10^{-2} by CDTS). This clarification also applies to Fig. 4 and Table III.

Fig. 3 shows the information outage probability as a function of the distance between users, when $P_{t,max} = 20$ dBm. As expected, in all schemes, the information outage probability increases when d_{ij} increases. Note that, CDTS is only operative for $d_{ij} \leq 25$ m, while RMTS and RCMTS allow to achieve $\mathcal{I}_o \leq 10^{-3}$ for $d_{ij} \leq 50$ m and for $d_{ij} \leq 75$ m, respectively, when $\mathcal{R}_o/W = 2$ bps/Hz. Even when the transmission rate of RMTS and RCMTS is doubled, these schemes allow to achieve a greater communication range (45 m from RMTS and 60 m from RCMTS), with a information outage probability less than or equal to 10^{-3}. Again, RCMTS outperforms all others schemes in terms of information outage, as well as in terms of spectral efficiency in short-range communications.

B. *Energy and spectral efficiency analysis*

Fig. 4 shows the minimum transmit power required as a function of the target information outage, when $d_{ij} = 50$ m. As expected, in all schemes the transmit power required increases when the constrain in terms of information outage increases. Note that, when $\mathcal{R}_o/W = 2$ bps/Hz, CDTS requires $P_t = 30$ dBm for a target information outage probability of 10^{-3}, while RMTS and RCMTS require $P_t = 14.5$ dBm and $P_t = 11$ dBm, respectively. It should be noted that RCMTS is more impacting when the constrains in terms of information outage increase, for example when the target information outage probability is 10^{-5}, RCMTS ($\mathcal{R}_o/W = 4$ bps/Hz) and RMTS ($\mathcal{R}_o/W = 2$ bps/Hz) require a similar transmit power ($P_t \approx 25$ dBm).

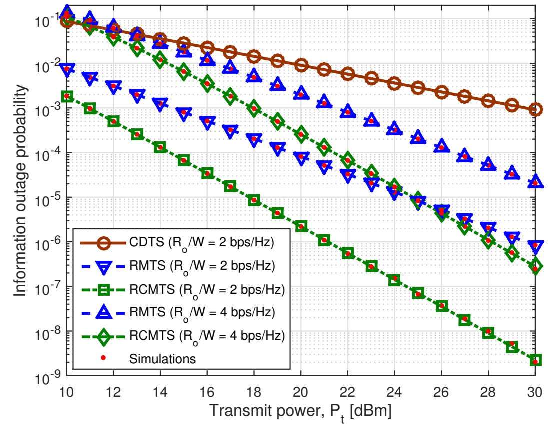

Fig. 2. Information outage as a function of the transmit power

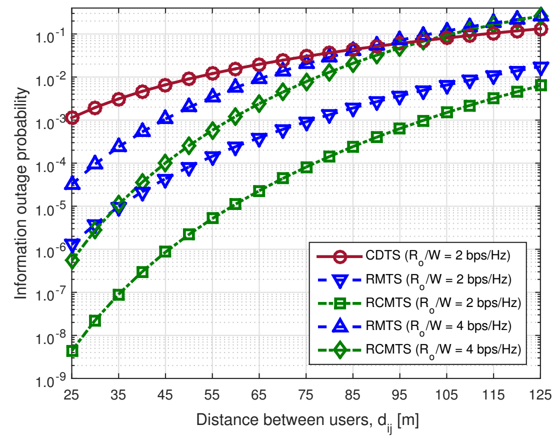

Fig. 3. Information outage as a function of the distance between users

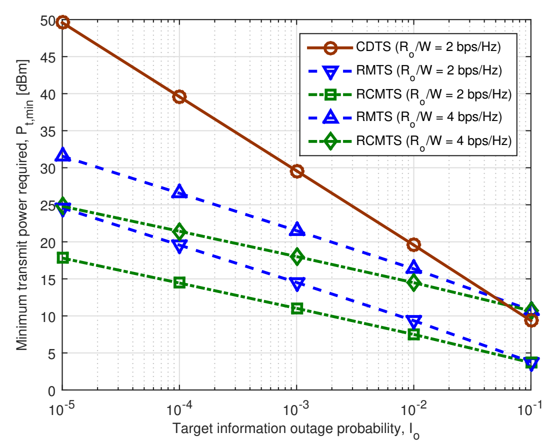

Fig. 4. Transmit power required as a function of the target information outage

Table III shows the amount of messages that can be transmitted per millijoule, according to each constraint of information outage probability. Again, RCMTS outperforms all others schemes in terms of energy efficiency. It should be noted

TABLE III. AMOUNT OF MESSAGES PER MILLIJOULE

Target information outage	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
CDTS ($\mathcal{R}_o/W = 2$ bps/Hz)	1	11	110	1 095	1 0435
RMTS ($\mathcal{R}_o/W = 2$ bps/Hz)	174	553	1 766	5 739	18 824
RCMTS ($\mathcal{R}_o/W = 2$ bps/Hz)	828	1 800	3 950	8 813	19 231
RMTS ($\mathcal{R}_o/W = 4$ bps/Hz)	70	221	707	2 296	7 530
RCMTS ($\mathcal{R}_o/W = 4$ bps/Hz)	331	720	1 580	3 525	7 692

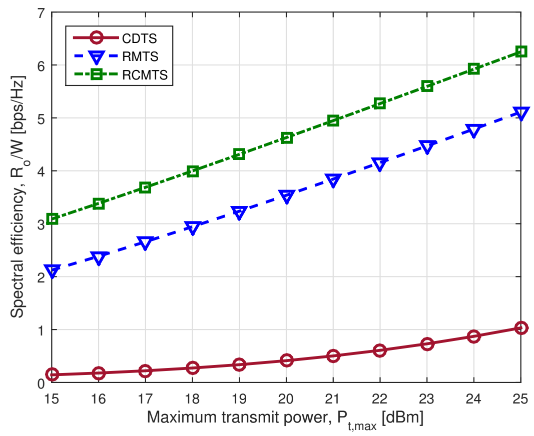

Fig. 5. Spectral efficiency as a function of the transmit power

that the cost of doubling the transmission rate is to increase five times the transmit power, according to (6), so the energy efficiency of RMTS and RCMTS (for $\mathcal{R}_o/W = 4$ bps/Hz) is 40% of those RMTS and RCMTS (for $\mathcal{R}_o/W = 2$ bps/Hz), respectively.

Fig. 5 shows the spectral efficiency as a function of the maximum transmit power, when $d_{ij} = 50$ m and the target information outage probability is 10^{-3}. As expected, in all schemes the spectral efficiency increases when the transmit power increases. Note that, RCMTS and RMTS outperform CDTS, specially for low transmit powers. The spectral efficiency of RCMTS is 1 bps/Hz more than RMTS for all transmit power values.

Finally, Fig. 6 shows the energy efficiency as a function of the maximum transmit power, when $d_{ij} = 50$ m and the target information outage probability is 10^{-3}. As expected, in all schemes the spectral efficiency decreases when the transmit power increases, due to the unfavorable tradeoff between transmission rate and transmit power. RCMTS is the best scheme in terms of energy efficiency, specially for low transmit power. Note that when $P_{\text{t,max}} = 20$ dBm, RCMTS allows to transmit 136 messages more than RMTS and almost six times the number of messages transmitted by CDTS, consuming one millijoule.

V. CONCLUSION AND FUTURE WORK

In this paper we proposed a novel transmission scheme based on coded redundant information. The results indicate that RCMTS is an effective non-cooperative alternative mode through which users can automatically revert back, when cooperation is not possible. The proposed method outperforms direct transmission and simple repetition schemes, in terms of reliability, as well as spectral and energy efficiency.

Future work will intend to investigate the performance of the proposed scheme in terms of end-to-end latency. Besides, we will compare the performance of the proposed scheme with those of retransmission and cooperative communication schemes, as well as with fountain codes, in scenarios with high node density and high mobile data traffic volume.

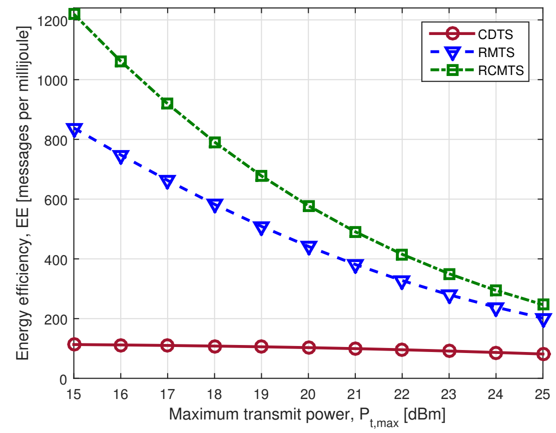

Fig. 6. Energy efficiency as a function of the transmit power

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