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Green Communication via Cooperative Protocols using Message-Passing Decoder over AWGN Channels

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Abstract

In wireless networks, the cooperative diversity is an implicit form of space diversity commonly used when other conventional transmit diversity methods might not be practical. It was largely proved that cooperative transmission, where a source and a relay cooperate to communicate with a unique destination, is power-efficient compared to the point-to-point transmission. However, the model considered when stating this conclusion is counting only the transmission power consumption. In this paper, we study the effect of taking into account not only the transmission power at each transmission node but also the processing power consumed in each reception node on the overall end-to-end performance. We formulate the optimization problem aiming to minimize the total power consumption in order to achieve a target performance constraint, where the total power consumption stands for the sum of the transmission power and the processing power consumed in the decoding (neglecting other forms of power consumption). Our analysis relies on the characterization of an information-theoretic bound on the decoding power of any modern code to achieve a specified bit error probability while operating at a certain gap from the capacity. As this bound is built on the sphere-packing analysis, the present study focuses on message-passing decoders. Using this theoretical framework, the improvement of well-known cooperative protocols over the original non-cooperative point-to-point system is reinvestigated in terms of total power consumption. Thanks to this theoretical framework, a new classification of the studied cooperative protocols is given revealing some surprising conclusions. In particular, the selective decode-and-forward protocol is no more constantly preferred to its simpler alternative, i.e. the decode-and-forward protocol.

I. INTRODUCTION

Power is one of the most important considerations in designing a highly reliable low-power wireless communication network [1]. The problem of minimizing the transmission power required for communicating over a point-to-point channel has been widely investigated. Generally, Shannon capacity theorem provides a quite successful

This work was done when H. Farès was with Université de Rennes 1, INRIA-IRISA.

interpretation of the minimum required transmission power to communicate reliably at the specified target rates for asymptotic blocklength regime. More specifically, to achieve a specified performance, channel coding strategies have been extensively adopted as efficient power saving methods. This saving in signal power is known as coding gain. Employing modern capacity-approaching coding schemes has been for long considered as the solution to optimize the performance of long distance wireless communication networks, where the processing power is legitimately unheeded. However, at shorter distances (which are of increasing interest), the processing power is comparable to, and can even dominate the transmission power. Therefore, the traditional intuition from these commonly used strategies can be misleading at short distances or when operating close to the channel capacity, at least in the context of coding. In these particular transmission conditions, the code choice affects not only the transmission power, but also the processing power consumed at the decoding. A significant interest is then addressed to an optimal partitioning between the transmission power and the encoding/decoding circuit power [2, 3].

From another hand, cooperative communication has emerged as an efficient concept that draws some of the benefits of multiple antenna devices over wireless channels, such as spatial diversity gain. The simplest cooperative scheme is the relay channel, introduced by van der Meulen in [4]: a relay assists a source by forwarding extra information to the destination. Since this pioneering work, a variety of cooperative protocols have been proposed. Recently, it was widely shown that cooperative systems are more power-efficient than non-cooperative transmission and many cooperative protocols have been classified [5–15]. However, to the best of our knowledge, all these works explore exclusively the transmission power in order to quantify the achieved spatial diversity gain with minimum user power consumption in terms of transmission power [16, 17]. Hence, this work aims to study the power efficiency of some popular relaying protocols when taking into account the decoding power of capacity-approaching channel codes, e.g. parallel or serially concatenated codes and low-density parity-check (LDPC) codes, for short-distance transmissions.

Relaying protocols can be generally classified as non-regenerative or regenerative. For the regenerative family we consider both decode-and-forward (DF) protocol, where the relay decodes and then retransmits the reencoded signal [5–7], and the selective decode and-forward (SDF) protocol, where only correctly decoded signal is reencoded before being retransmitted [9, 10]. For the non-regenerative family, we consider both amplify-and-forward (AF) protocol, where the relay simply amplifies the signal before retransmitting with a fixed amplification factor [10, 14], and adaptive amplify-and-forward (AAF) protocol, where the amplification factor is considered as a second optimization parameter to be adapted to the transmission conditions [11, 13].

We investigate then the effect of taking the decoding power into consideration on the end-to-end total power consumption of the commonly used relaying protocols listed above. The optimization problem is cast as the minimization of the total power under a certain performance constraint (a target frame error probability is fixed). This study can subvert usual conclusions in relaying protocols classification, since decoding power is counted twice (at the relay as well as at the destination) for the regenerative family. We consider a message-passing decoder at the receiver side and we use the theoretical bound on the decoding power given in [18]. Also, we consider short-range wireless communications with a large bandwidth where the transmission power does no more dominate the

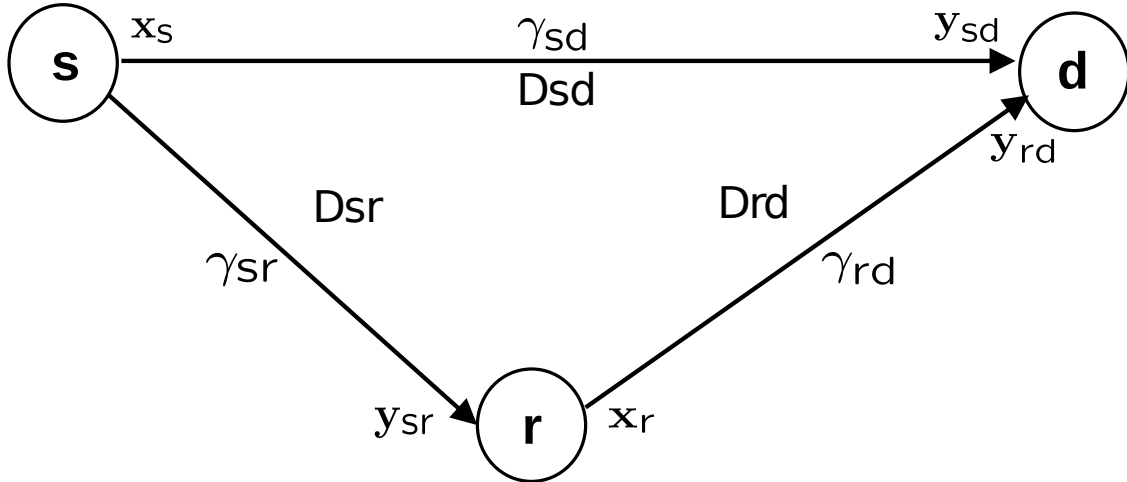


Fig. 1. A wireless relay channel.

total power consumption and more insights have to be conducted on the decoding power [19, 20]. We analyze the improvement of the studied cooperative protocols over the original non-cooperative point-to-point system in terms of total power consumption. We define the cooperation power gain, which serves as decision parameter to determine the geometric conditions under which cooperative protocols are useful. Moreover, this geometrical framework is adopted in order to determine how the decoding power affects the benefits of cooperation.

The remainder of this paper is organized as follows. The system model is described in Section II. Section III introduces four different optimization problems minimizing the total power consumption of DF, SDF, AF and AAF protocols. Finally, numerical results and performance discussions are provided in Section IV, and Section V draws some conclusions.

II. SYSTEM MODEL

We consider the wireless two-hop relay channel with one source, one relay and one destination as depicted in Fig. 1. The purpose of the system is to convey source messages to the destination with the help of an intermediate relay. The relay receives the overhead information and assists the source by either forwarding the regenerated version of the original information (for DF and SDF protocols) or a weighted version of the received signal (for AF or AAF protocols). The destination subsequently receives both the source and the relay transmissions and apply an equal-gain combining before decoding.

In practice, terminals (for instance the relay) cannot transmit and receive at the same time and over the same frequency band, therefore the channels are assumed to be orthogonal and consequently nodes operate in time division duplex mode. We assume three independent binary additive white Gaussian noise (AWGN) channels for the source-to-destination (s-d link), source-to-relay (s-r link) and relay-to-destination (r-d link). We denote by P_t

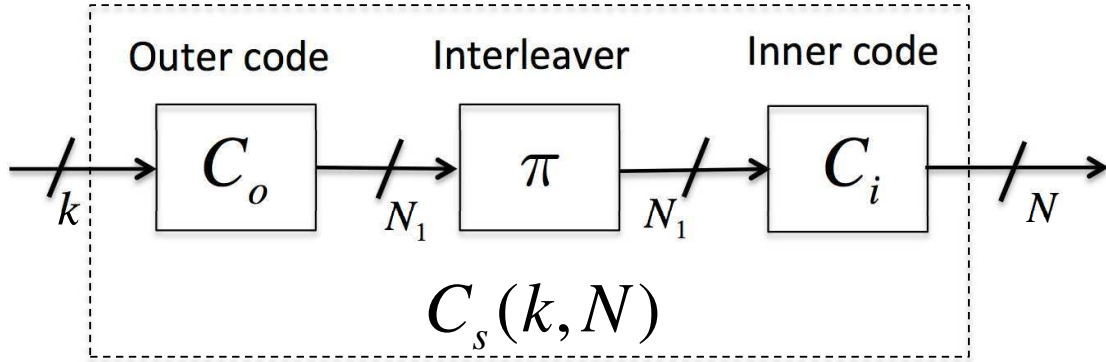


Fig. 2. Serially concatenated block code $C_s(k, N)$.

the transmission power at both the source and the relay, the received power is given then by

$$P_r = gP_t = \left(\frac{c}{f_c D}\right)^\alpha P_t = \lambda D^{-\alpha} P_t, \quad (1)$$

where g is the channel power gain modeling the path loss, c is the speed of light, f_c is the carrier frequency, $\lambda = (c/f_c)^\alpha$, D is the distance between the transmission and the reception nodes ($D = D_{sd}$ for the s-d link, $D = D_{sr}$ for the s-r link and $D = D_{rd}$ for the r-d link) and α is the path-loss exponent, which is often assumed to be $2 \leq \alpha \leq 6$ [21].

The unit-power input message \mathbf{x}_s is summed to the complex noise $\mathbf{z}_{sr} \sim \mathcal{CN}(0, \sigma_0^2)$ over the s-r link and to $\mathbf{z}_{sd} \sim \mathcal{CN}(0, \sigma_0^2)$ over the s-d link resulting in the respective outputs \mathbf{y}_{sr} and \mathbf{y}_{sd} , represented by

$$\mathbf{y}_{sr} = \sqrt{\lambda D_{sr}^{-\alpha} P_t} \mathbf{x}_s + \mathbf{z}_{sr}, \quad (2)$$

$$\mathbf{y}_{sd} = \sqrt{\lambda D_{sd}^{-\alpha} P_t} \mathbf{x}_s + \mathbf{z}_{sd}, \quad (3)$$

with $\sigma_0^2 = k_B T W$ the Gaussian thermal noise variance, where k_B is the Boltzmann constant, T is the room temperature, and W is the signal bandwidth. The source node employs a serially concatenated block code (SCBC) $C_s(k, N)$ of rate $R_{C_s} = k/N$. The encoder maps the binary information messages \mathbf{u} of length k to codewords \mathbf{x}_s of length N . The SCBC is obtained by concatenating an outer code $C_o(k, N_1)$ with an inner code $C_i(N_1, N)$ through an interleaver π of length N_1 [25]. The scheme of the $C_s(k, N)$ code is shown in Fig. 2. Furthermore, the study is restricted to Gaussian input distributions.

A. Amplify-and-Forward protocols

For the AF protocol, the relay helps to forward \mathbf{y}_{sr} to the destination by scaling this signal with the amplification gain \mathcal{A} . The received signal at the destination after the cooperative phase, can be expressed as

$$\mathbf{y}_{rd} = \mathcal{A} \sqrt{\lambda D_{rd}^{-\alpha} P_t} \mathbf{y}_{sr} + \mathbf{z}_{rd}, \quad (4)$$

where $\mathbf{z}_{rd} \sim \mathcal{CN}(0, \sigma_0^2)$ is the complex noise added by the destination over the r-d link.

Substituting \mathbf{y}_{sr} expression, we obtain

$$\mathbf{y}_{\text{rd}} = \mathcal{A}\lambda\sqrt{D_{\text{rd}}^{-\alpha}D_{\text{sr}}^{-\alpha}P_t}\mathbf{x}_s + \mathcal{A}\sqrt{\lambda D_{\text{rd}}^{-\alpha}P_t}\mathbf{z}_{\text{sr}} + \mathbf{z}_{\text{rd}}. \quad (5)$$

The noise term $\mathbf{z}'_{\text{rd}} = \mathcal{A}\sqrt{\lambda D_{\text{rd}}^{-\alpha}P_t}\mathbf{z}_{\text{sr}} + \mathbf{z}_{\text{rd}}$ has the variance $\sigma_0'^2 = [|\mathcal{A}|^2 \lambda D_{\text{rd}}^{-\alpha}P_t + 1] \sigma_0^2$.

Conventionally, the amplification gain \mathcal{A} satisfies the power constraint given by

$$|\mathcal{A}|^2 \leq \frac{1}{\lambda D_{\text{rd}}^{-\alpha}P_t + \sigma_0^2}. \quad (6)$$

For the AF protocol, the choice of the value of the amplification gain is not free and it is set to the maximum possible value, we assume then that $|\mathcal{A}| = |\mathcal{A}_{\text{max}}| = \sqrt{\frac{1}{\lambda D_{\text{rd}}^{-\alpha}P_t + \sigma_0^2}}$. As \mathcal{A}_{max} is a function of the transmission power P_t , we will see latter that the total power consumption is then minimized subject to a unique parameter, which is the transmission power P_t .

The signal-to-noise ratio (SNR) for the s-r, s-d and r-d links are given by $\gamma_{\text{sr}} = \lambda D_{\text{sr}}^{-\alpha} \frac{P_t}{\sigma_0^2}$, $\gamma_{\text{sd}} = \lambda D_{\text{sd}}^{-\alpha} \frac{P_t}{\sigma_0^2}$ and $\gamma_{\text{rd}} = \lambda D_{\text{rd}}^{-\alpha} \frac{P_t}{\sigma_0^2}$, respectively. The SNR of the whole two-hop cooperative link is then given by

$$\gamma_{\text{srd}} = \frac{|\mathcal{A}|^2 \lambda^2 D_{\text{sr}}^{-\alpha} D_{\text{rd}}^{-\alpha} P_t^2}{\sigma_0'^2} = \frac{|\mathcal{A}|^2 \gamma_{\text{sr}} \gamma_{\text{rd}}}{|\mathcal{A}|^2 \gamma_{\text{rd}} + 1/\sigma_0^2}. \quad (7)$$

By substituting the amplification gain by its exact expression, the SNR of the cooperative link for AF protocol becomes

$$\gamma_{\text{srd}} = \frac{\gamma_{\text{sr}} \gamma_{\text{rd}}}{1 + \gamma_{\text{sr}} + \gamma_{\text{rd}}}. \quad (8)$$

For the AAF protocol, the choice of the amplification gain \mathcal{A} is variable, it depends heavily on the transmission conditions and can change from one transmission to another one and hence can be tuned such that the system performance is optimized subject to the power constraint given in (6). In the present study, the optimization is given in terms of a minimum total power consumption required to achieve a target frame error probability.

B. Decode-and-Forward protocols

For the DF protocol, the relay exploits the received observation \mathbf{y}_{sr} in order to detect the source message, reencodes it using the same $\mathcal{C}_s(k, N)$ encoder and finally forwards the estimated codeword \tilde{x}_s to the destination, which receives

$$\mathbf{y}_{\text{rd}} = \sqrt{\lambda D_{\text{rd}}^{-\alpha} P_t} \tilde{x}_s + \mathbf{z}_{\text{rd}}. \quad (9)$$

The destination attempts to decode the source messages based on the noisy observations over the direct s-d link as well as the cooperative s-r-d link, \mathbf{y}_{sd} and \mathbf{y}_{rd} , respectively. For instance, the observation \mathbf{y}_{rd} is the output of a virtual memoryless channel with input x_s and SNR $\gamma'_{\text{rd}} \leq \gamma_{\text{rd}}$ [23, 24]. Therefore, this virtual channel implicitly models the relay decoding errors via a degraded SNR $\gamma'_{\text{rd}} = \tau \gamma_{\text{rd}}$, where $0 < \tau \leq 1$ is an attenuation factor modeling the subsum of channel quality on s-r link and r-d link and the detection errors at the relay. The attenuation factor τ is function of the channel quality of the s-r link (γ_{sr}) and can be tuned such that the virtual channel approximation best matches the actual two-hop cooperative channel involving the s-r and r-d links.

For the SDF protocol, in the cooperative phase, if the relay correctly detects the received message (using a cyclic redundancy check code), then it will forward it to the destination; otherwise, the relay will remain silent to avoid the propagation of errors [22]. In this last case, the destination will then attempt to decode the source messages exclusively based on the received signal over the s-d link, \mathbf{y}_{sd} .

Furthermore, for the analysis of the decoder power consumption given in Section III, we need an information-theoretic approximation of the frame error probability (P_e) and the bit error probability P_{eb} of the SCBC \mathcal{C}_s channel encoder. We can use then the upper-bounds [25] given, respectively, by

$$P_e(\gamma) \leq \frac{1}{2} \sum_{d=df}^N A_{w,d}^{\mathcal{C}_s} \operatorname{erfc} \left(\sqrt{d R_{C_s} \gamma} \right), \quad (10)$$

$$P_{eb}(\gamma) \leq \frac{1}{2} \sum_{w=1}^k \frac{w}{k} A_{w,d}^{\mathcal{C}_s} \operatorname{erfc} \left(\sqrt{d R_{C_s} \gamma} \right), \quad (11)$$

where df is the free distance of the channel code, defined as the minimum Hamming distance over all error events; and $A_{w,d}^{\mathcal{C}_s}$ is the input-output weight enumerator (IOWE) of the overall SCBC \mathcal{C}_s . Using the uniform-interleaver approach [25] and averaging over all possible interleavers π , the IOWE of the overall SCBC \mathcal{C}_s is written as

$$A_{w,d}^{\mathcal{C}_s} = \sum_{d_1=0}^{N_1} \frac{A_{w,d_1}^{\mathcal{C}_o} A_{d_1,d}^{\mathcal{C}_i}}{\binom{N_1}{d_1}}, \quad (12)$$

with $\binom{N_1}{d_1}$ denotes the binomial coefficient, i.e., d_1 -combinations from N_1 elements. $A_{w,d_1}^{\mathcal{C}_o}$ denotes the IOWE of the outer code \mathcal{C}_o , giving the number of codewords of weight d_1 generated by information messages of weight w . Likewise, $A_{d_1,d}^{\mathcal{C}_i}$ denotes the IOWE of the inner coder \mathcal{C}_i , giving the number of codewords of weight d generated by information messages of weight d_1 .

III. TOTAL POWER OPTIMIZATION UNDER PERFORMANCE CONSTRAINT

The optimization problem aims to minimize the total power consumption subject to a given performance constraint.

It is important to note that the present optimization problem is not new and it was addressed in many precedent researchs. However, up to now, all results are given when taking only the transmission power into consideration. Hence, to get closer to the reality, our study aims rather to minimize the total power consumption including the decoding power according to the power consumption model described in [18], specific to a message-passing decoder where the decoder implementation is abstracted as a decoder-connectivity graph.

By generalizing the result in [18], at each receiver node, the decoding power P_{dec} can be approximated by its lower-bound given by

$$P_{\text{dec}}(\gamma) \approx \frac{\beta}{R_{C_s}} \left[Q + \frac{\ln \left(\frac{\ln \left(\frac{1}{K P_{eb}(\gamma)} \right)}{\ln(2)} \right)}{\ln(2)} - \frac{2 \ln(C(\gamma) - R_{C_s})}{\ln(2)} \right] \quad (13)$$

with γ is the operating SNR function of the transmission power P_t , $\beta = E_{\text{node}} R_{\text{dec}}$, $Q = \frac{\log_2(\frac{\zeta-2}{\zeta})}{\log_2(\zeta-1)}$, where:

- E_{node} is the energy consumption per iteration of one processing element (PE) in the decoder graph.
- R_{dec} is the decoder throughput
- ζ is the maximum connectivity degree, i.e., the maximum number of neighbors of each PE.
- K is a constant that depends on the channel [18].
- P_{eb} is the target bit error probability. It represents the bit error probability over a transmission link, which can be approximated by the union bound of the utilized SCBC, as given by (11), using the appropriate SNR expression.
- $C(\gamma)$ is the channel capacity at the end of a transmission phase over a specific link (s-r, s-d or r-d link).

A. Amplify-and-Forward

For the AF protocol, the portion of power consumed at the transmission consists of the transmission power at the source $P_t^s = P_t$ and the transmission power at the relay given by

$$P_t^r = |\mathcal{A}|^2 P_t \mathbb{E} \left[|y_{\text{sr}}|^2 \right] = P_t, \quad (14)$$

where $\mathbb{E}[\cdot]$ is the expectation operator, and the underscript r refers to the relay.

As the destination is the unique node performing the decoding of \mathcal{C}_s code, the power consumed at decoding is taken into account only once, P_{dec}^d (here, the underscript d refers to the destination). Furthermore, the destination performs an equal-gain combining between received signals from both source and relay, the operating SNR is then $\gamma^{\text{AF}} = \gamma_{\text{sd}} + \gamma_{\text{srd}}$, where γ_{srd} is the equivalent SNR of the two-hop cooperative link expressed by (8). The expression of γ^{AF} can be simplified as

$$\gamma^{\text{AF}} = \gamma_{\text{sd}} + \gamma_{\text{sr}} \left(1 + \frac{\gamma_{\text{rd}}}{1 + \gamma_{\text{sr}} + \gamma_{\text{rd}}} \right). \quad (15)$$

Hence, the total power consumption can be formulated as

$$P_{\text{tot}}^{\text{AF}} = 2P_t + P_{\text{dec}}^d (\gamma^{\text{AF}}). \quad (16)$$

Consequently, the optimization problem can be formulated as

$$\begin{aligned} \min_{P_t} \quad & P_{\text{tot}}^{\text{AF}} = 2P_t + P_{\text{dec}}^d (\gamma^{\text{AF}}) \\ \text{s.t.} \quad & P_e(\gamma^{\text{AF}}) \leq \varepsilon, \end{aligned} \quad (17)$$

where ε is the target error probability. Note that, since the operating SNR γ^{AF} is function of the transmission power P_t , the decoding power is also function of P_t .

B. Adaptive Amplify-and-Forward

For the AAF protocol, as the amplification power is variable, the transmission power at the relay is then function of \mathcal{A} and is given by

$$P_t^r = |\mathcal{A}|^2 P_t \mathbb{E} \left[|y_{\text{sr}}|^2 \right] = |\mathcal{A}|^2 P_t (\lambda D_{\text{sr}}^{-\alpha} P_t + \sigma_0^2). \quad (18)$$

As for the AF protocol, the direct link contribution as well as the two-hop cooperative link contribution are combined before performing decoding at the destination. Therefore, the operating SNR is obtained from summing both γ_{sd} and γ_{srd} (given in (7)) and consequently can be expressed by

$$\gamma^{\text{AAF}} = \gamma_{sd} + \gamma_{sr} \left(1 + \frac{|\mathcal{A}|^2 \gamma_{rd}}{|\mathcal{A}|^2 \gamma_{rd} + 1/\sigma_0^2} \right). \quad (19)$$

γ^{AAF} is thereafter used to compute the power consumed by the destination in decoding, $P_{\text{dec}}^{\text{d}}(\gamma^{\text{AAF}})$.

The total power consumption can be subsequently formulated as

$$P_{\text{tot}}^{\text{AAF}} = P_t + |\mathcal{A}|^2 P_t (\lambda D_{\text{sr}}^{-\alpha} P_t + \sigma_0^2) + P_{\text{dec}}^{\text{d}}(\gamma^{\text{AAF}}). \quad (20)$$

Finally, the optimization problem can be formulated as

$$\begin{aligned} \min_{P_t, \mathcal{A}} \quad & P_{\text{tot}}^{\text{AAF}} = P_t + |\mathcal{A}|^2 P_t (\lambda D_{\text{sr}}^{-\alpha} P_t + \sigma_0^2) + P_{\text{dec}}^{\text{d}}(\gamma^{\text{AAF}}) \\ \text{s.t.} \quad & P_e(\gamma^{\text{AAF}}) \leq \varepsilon \\ & |\mathcal{A}|^2 \leq |\mathcal{A}_{\text{max}}|^2 = \frac{1}{\lambda D_{\text{sr}}^{-\alpha} P_t + \sigma_0^2}. \end{aligned} \quad (21)$$

Note that the amplification factor \mathcal{A} is used as a second tuning parameter which offers a more accurate optimization and better results. However, this considerably increases the complexity of the optimization problem.

C. Decode-and-Forward

For DF protocol, besides the destination which performs decoding based on \mathbf{y}_{sd} and \mathbf{y}_{rd} , the received signals over direct and cooperative link; the relay alike performs decoding based on the noisy observation \mathbf{y}_{sr} . The power consumed at decoding is then taken into account twice: $P_{\text{dec}}^{\text{d}}$ accounting for the decoding power consumed by the destination and $P_{\text{dec}}^{\text{r}}$ denoting the decoding power consumed by the relay.

At the relay side, the operating SNR used to estimate the decoding power consumption is that observed over the s-r link, i.e., γ_{sr} . However, at the destination side, an equal-gain combining of \mathbf{y}_{sd} and \mathbf{y}_{rd} is prior to the decoding operation, the operating SNR used to predict the decoding power consumption is given then by

$$\gamma^{\text{DF}} = \gamma_{sd} + \gamma'_{rd, \text{opt}}. \quad (22)$$

As the relay is forwarding the estimated codeword \tilde{x}_s , the whole two-hop cooperative link (s-r-d link) can be seen as an equivalent virtual direct link with a degraded SNR $\gamma'_{rd} = \tau \gamma_{rd}$, where the tuning attenuation factor can be optimized leading to τ_{opt} and consequently $\gamma'_{rd, \text{opt}} = \tau_{\text{opt}} \gamma_{rd}$ is the appropriate channel quality that closely approaches the performance of the DF protocol and correctly includes error propagations. Furthermore, τ_{opt} is a function of s-r channel quality and can be calculated off-line before deployment [23].

The total power consumption can be then formulated as

$$P_{\text{tot}}^{\text{DF}} = 2P_t + P_{\text{dec}}^{\text{r}}(\gamma_{sr}) + P_{\text{dec}}^{\text{d}}(\gamma^{\text{DF}}). \quad (23)$$

Hence, the optimization problem can be formulated as

$$\begin{aligned} \min_{P_t} \quad & P_{\text{tot}}^{\text{DF}} = 2P_t + P_{\text{dec}}^r(\gamma_{\text{sr}}) + P_{\text{dec}}^d(\gamma^{\text{DF}}) \\ \text{s.t.} \quad & P_e(\gamma^{\text{DF}}) \leq \varepsilon. \end{aligned} \quad (24)$$

D. Selective Decode-and-Forward

According to the two different states at the relay (forwarding correctly decoded source messages or keeping silent), the destination performs decoding based either on the direct link contribution only (y_{sd}) or on the combined version of both received signals y_{sd} and y_{rd} . For the last case, γ_{rd} perfectly estimated the channel quality of the two-hop cooperative link since no error propagation is possible for the SDF protocol, and the operating SNR is then $\gamma^{\text{SDF}} = \gamma_{\text{sd}} + \gamma_{\text{rd}}$. However, the decoding power consumed at the relay is always involved in consumption model since the decoding at the relay is continuously performed in order to make decision either to cooperate or not.

The total power consumption is obtained by

$$\begin{aligned} P_{\text{tot}}^{\text{SDF}} = & P_t + P_{\text{dec}}^r(\gamma_{\text{sr}}) + P_e(\gamma_{\text{sr}})P_{\text{dec}}^d(\gamma_{\text{sd}}) \\ & + (1 - P_e(\gamma_{\text{sr}})) [P_t + P_{\text{dec}}^d(\gamma_{\text{sd}} + \gamma_{\text{rd}})]. \end{aligned} \quad (25)$$

Therefore, the optimal total power consumption is the result of the following optimization problem

$$\begin{aligned} \min_{P_t} \quad & P_{\text{tot}}^{\text{SDF}} \\ \text{s.t.} \quad & P_e(\gamma_{\text{sr}})P_e(\gamma_{\text{sd}}) + (1 - P_e(\gamma_{\text{sr}})) P_e(\gamma_{\text{sd}} + \gamma_{\text{rd}}) \leq \varepsilon. \end{aligned} \quad (26)$$

IV. POWER EFFICIENCY ANALYSIS

In this section, we give the performance of AF, AAF, DF and SDF cooperative protocols in terms of cooperation power gain with respect to a reference system which is the non-cooperative point-to-point transmission. For a fixed channel code, the cooperation power gain, is defined as

$$G_{P_{\text{tot}}}^{\text{CoopTx}} = \frac{P_{\text{tot,opt}}^{\text{CoopTx}}}{P_{\text{tot,opt}}^{\text{DirectTx}}}, \quad (27)$$

where $P_{\text{tot,opt}}^{\text{CoopTx}} = P_{\text{tot,opt}}^{\text{AF}}, P_{\text{tot,opt}}^{\text{AAF}}, P_{\text{tot,opt}}^{\text{DF}}$ or $P_{\text{tot,opt}}^{\text{SDF}}$ is the solution of the optimization problems given by (17), (21), (24) or (26), respectively. These optimization resolutions are achieved using heuristical methods. Furthermore, $P_{\text{tot,opt}}^{\text{DirectTx}}$ is the minimum power consumption of the non cooperative transmission computing both the transmission power and the processing power used for decoding. In [19], it has been proved that $P_{\text{tot,opt}}^{\text{DirectTx}}$ is achieved for an optimal partitionning of the total consumption between the transmission and the iterative decoding, i.e., the solution is then transmitting away from the Shannon limit with some particular penalty in order to obtain a tradeoff between power consumed in transmission and in decoding. This optimum is chosen in order to alleviate the material constraints on the complexity of decoding and subsequently significantly reduce the power consumed by the decoder circuit.

For all examples here (except the curves presented in Fig. 6 using an LDPC channel code with rate 1/2), we consider an SCBC composed of \mathcal{C}_o , a parity check code (3,4), followed by \mathcal{C}_i , a Hamming code (4,7). The choice

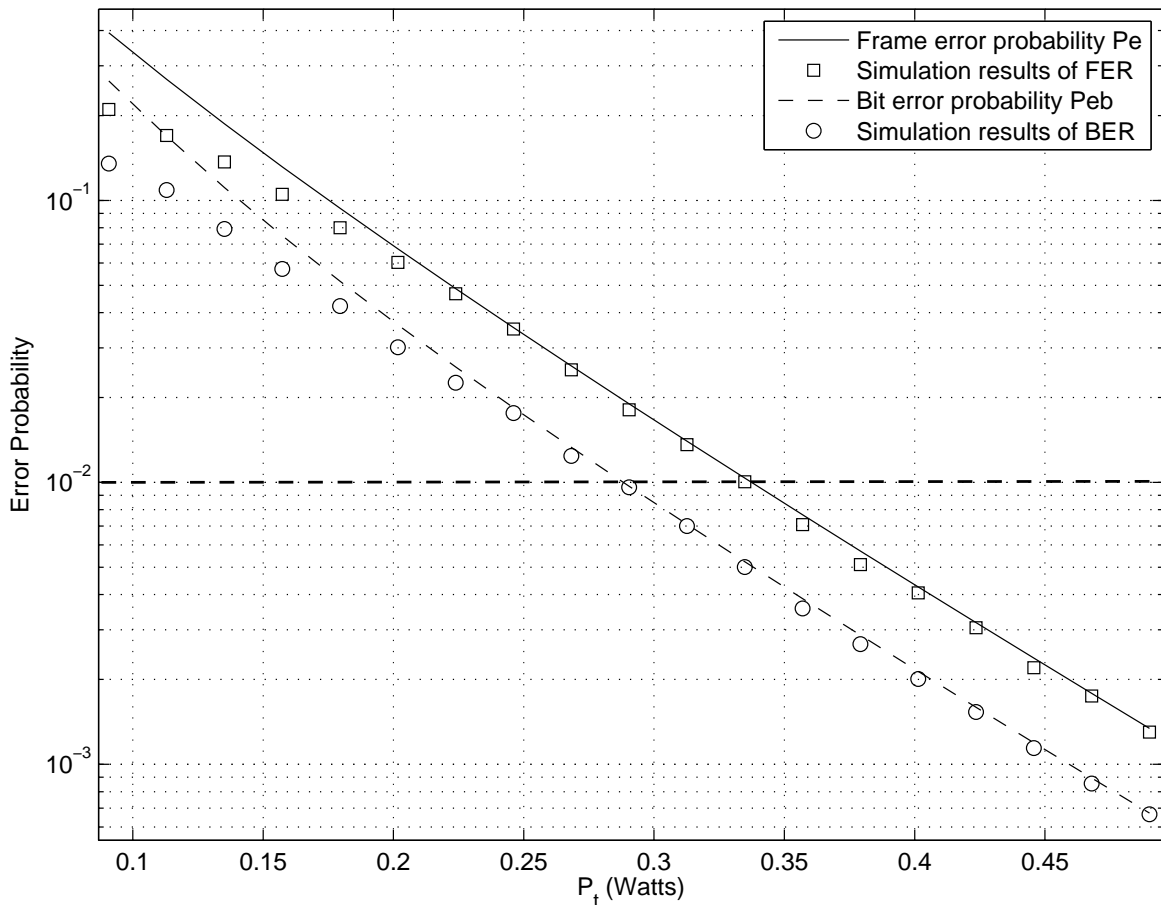


Fig. 3. Union bound of frame error probability and bit error probability compared, respectively, to the simulation results of frame error rate and bit error rate for a point-to-point non cooperative transmission where $D_{sd} = 15$ m and using The SCBC code $\mathcal{C}_s(3, 7)$.

of a short interleaver promotes the tightness of the union bounds of the SCBC for low SNRs, and thus the validity of our study. The simulation results are given for the same transmission context fixed in [19], where it has been shown that the decoding power can not be ignored with respect to the transmission power. We assume a short range wireless communication between a source s and a destination d separated with a distance $D_{sd} = 15$ m, with a large bandwidth $W = 1$ GHz where the transmission power is usually low (in the order of milliwatts). The carrier frequency is $f_c = 60$ GHz, the thermal noise power density is $\sigma_0^2 = k_B T W$ ($T = 300$, the room-temperature in kelvins), $K = 0.5$ and the path-loss exponent $\alpha = 3$. We assume that the maximum connectivity $\xi = 4$, the decoding throughput $R_{dec} = 1.3$ Gbps and $E_{node} = 1$ pJ. Results are given for $\varepsilon \leq 10^{-2}$ (low target frame error probability), where the used union bounds in (10) and (11) are verified to be tight enough as illustrated in Fig. 3. For instance, we plot in Fig. 3 the theoretical union bounds of the frame error probability as well as the bit error

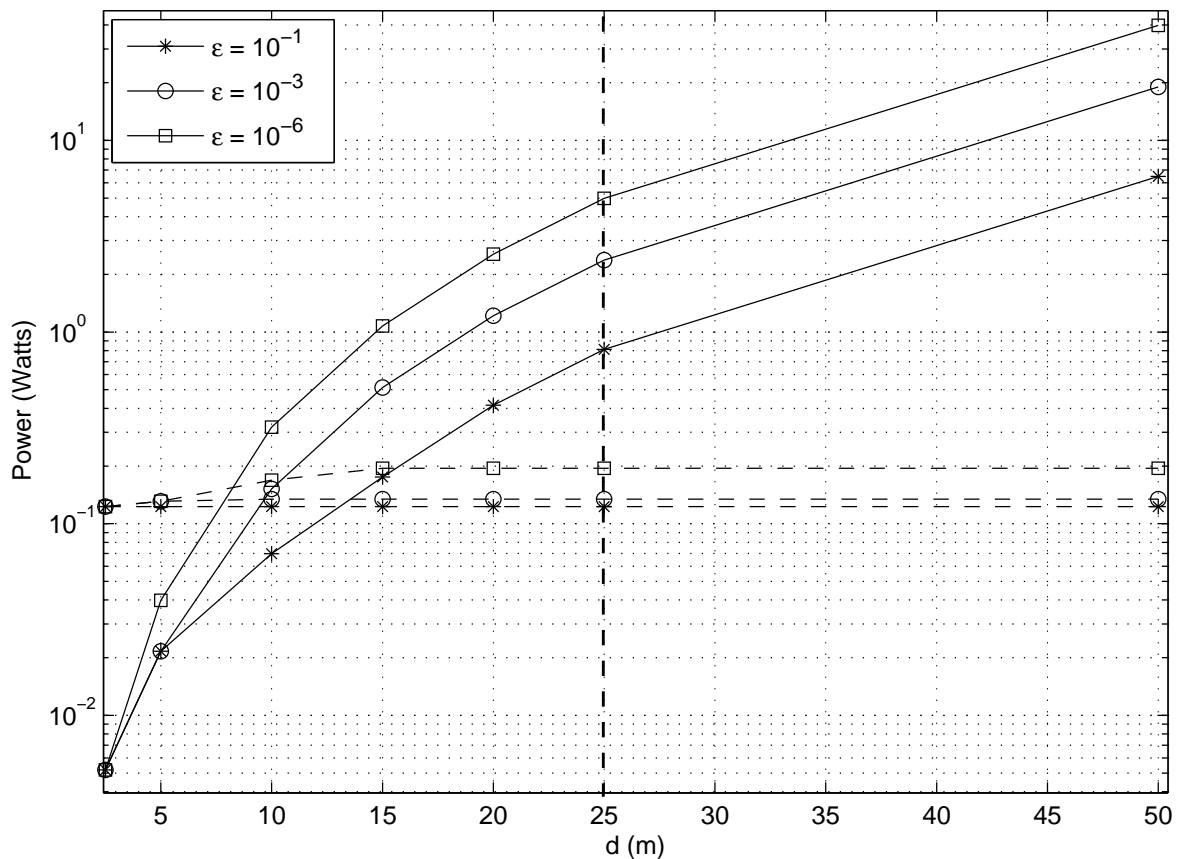


Fig. 4. Optimized transmit (solid lines) and decoding (dashed lines) powers versus source-to-destination distance of a non-cooperative transmission for various values of ϵ .

probability compared to the simulation results of frame error rate (FER) and bit error rate (BER) for the transmission context described above without the assistance of the relay node.

All these parameters used to describe the considered transmission scenario, are chosen such as to meet the requirements of the IEEE 802.11ad standard, commonly called the WiGig standard [26]. However, the study is quite general to be applicable for other standards operating with large bandwidth (in the order of gigahertz) and ensuring multi-gigabit data rates. Another possible case of use of this specific transmission context (to meet the communication requirements for considering the decoding power) can be the millimeter-wave propagation for fifth-generation (5G) cooperative small-cell networks [27, 28].

In Fig. 4, we illustrate the transmission scenario (in terms of source-to-destination distance) under which the decoding power is comparable to the transmission power for the context of a non-cooperative system. The results depicted in this figure confirm the conclusion given in [19], affirming that taking into consideration the decoding

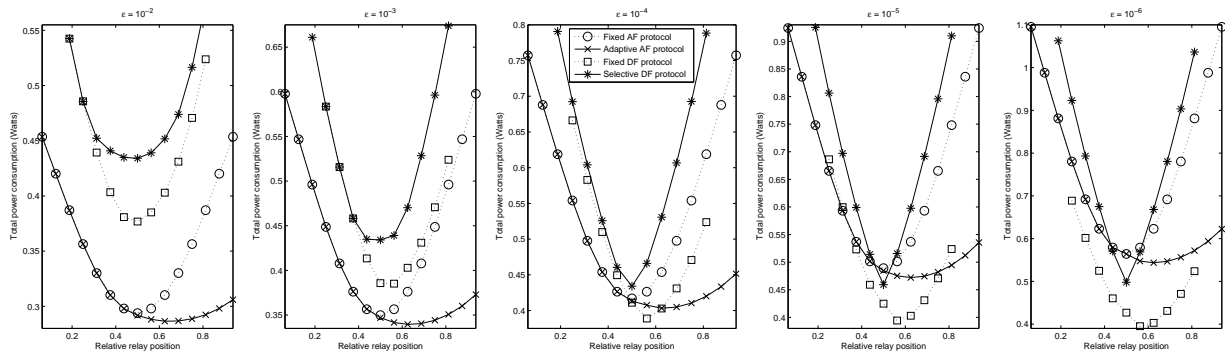


Fig. 5. Optimal total power consumption of cooperative protocols as a function of the relative relay position (d_r) over the linear scenario for $D_{sd} = 15$ m and for various values of ε , using the SCBC code $C_s(3, 7)$.

power to evaluate the system power efficiency is particularly relevant for short-range communication. For instance, for distances $d \leq 25$ m, there is at least one performance constraint for which the ratio between transmission power and decoding power is not greater than 10. The decoding power is then no more negligible compared to the transmission power.

In the following, we adopt two different geometrical setups for the cooperative system. First, we consider a wireless relay system where the source s is fixed and the relay r is moving on the same line from s towards the destination d . Taking into account the path loss effect, the received SNRs over s - r and r - d links are function of the fixed received SNR over the s - d link (γ_{sd}), consequently are given, respectively, by $\gamma_{sd}d_r^{-\alpha}$ and $\gamma_{sd}(1 - d_r)^{-\alpha}$, where d_r is the relative relay position (normalized by D_{sd}).

In Fig. 5, we examine the optimal total power consumption of cooperative (AF, AAF, DF, SDF) protocols as a function of d_r , for different target performance constraints $\varepsilon = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ and 10^{-6} .

Regardless the location of r , AAF always benefits to the cooperative system with respect to AF, which is a non-surprising result. Since the amplification factor is considered as a second tuning parameter in the optimization problem, a more power-efficient solution can be found and at worst the AAF protocol performs like the AF protocol ($d_r \leq 0.5$). For this particular region, at the optimum, the power constraint is saturated ($\mathcal{A}_{opt} = \mathcal{A}_{max}$) and the AAF protocol performs exactly like the AF protocol. For $d_r > 0.5$ region, where errors at relay are more frequent due to a longer distance propagation, we need to amplify less the signal at the relay node ($\mathcal{A}_{opt} < \mathcal{A}_{max}$) in order to restrict errors amplification from one side and to relax constraints on the decoding at the destination from another side. This yields to sizable power savings especially for low target frame error probability. Furthermore, since $\mathcal{A}_{opt} < \mathcal{A}_{max}$, the power constraint in the optimization problem of (21) is no more saturated. This explains the flatness of the AAF curve when $d_r > 0.5$. We notice also that the best relay location for AF protocol is exactly the middle of the distance between the source and the destination. However, the introduction of the amplification factor as an extra degree of freedom on the optimization problem for the AAF protocol shifts the optimal relay position close to the destination, a position which is quite independent from the target performance constraint.

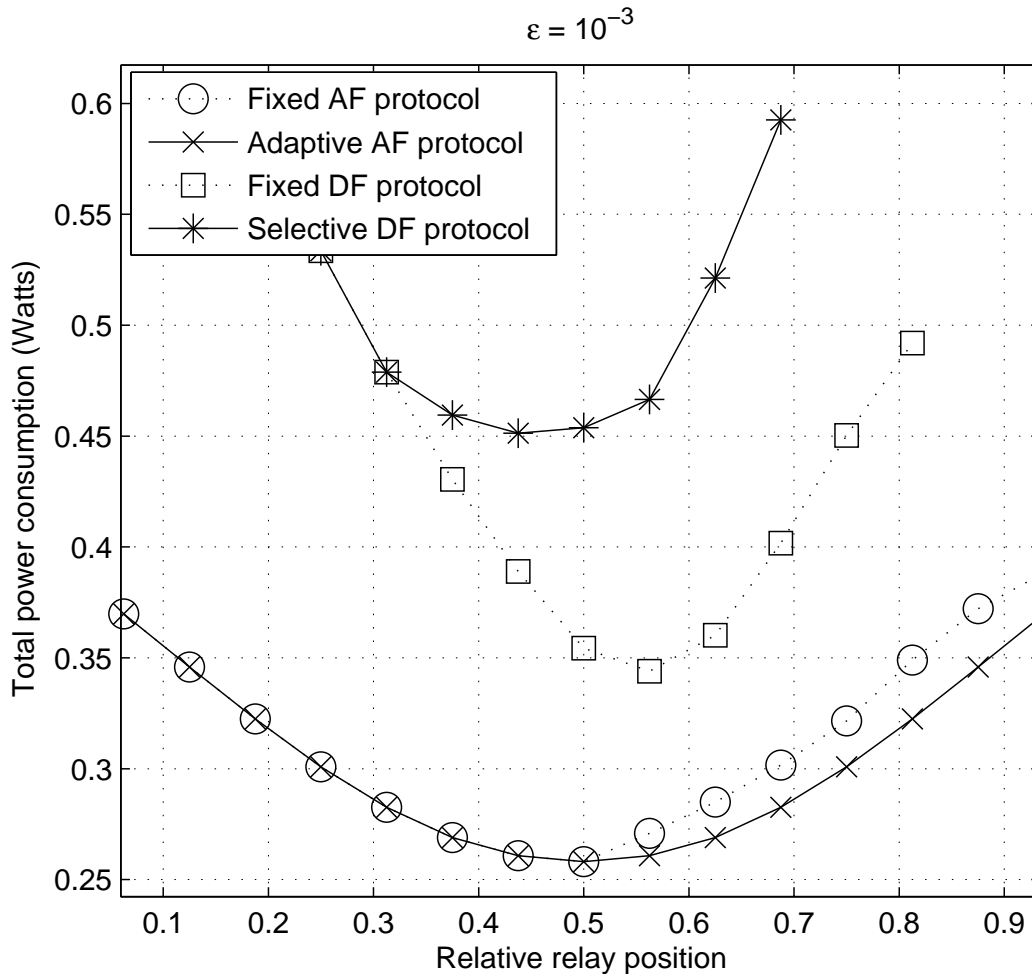


Fig. 6. Optimal total power consumption of cooperative protocols over the linear scenario for $D_{sd} = 15$ m, fixing the target performance constraint to 10^{-3} and using an 1/2-LDPC code adopted in the 802.11ad standard.

For the DF protocols category, the most important result, which is different from the well-known one obtained for power consumption optimization taking only into account the transmission power, is the superiority of the DF protocol with respect to SDF protocol. This surprising finding stems from the significant power saving brought by the decoding at the destination using the operating SNR $\gamma^{DF} = \gamma_{sd} + \gamma'_{rd,opt}$. Hence, for DF protocol, combining signals from both the source and the relay greatly relaxes the material constraints on the decoder circuit at the destination and can largely compensate the extra transmission power spent by the relay when forwarding all the time the overhead signal from the source even when errors are noticed (already taken into account by the degraded SNR of the two-hop cooperative link). Therefore, the DF protocol with a fixed behaviour at the relay is preferred to the SDF protocol. This is explained by the following inequality

$$P_e(\gamma_{sr})[P_t + P_{dec}^d(\gamma_{sd} + \gamma'_{rd,opt})] \ll P_e(\gamma_{sr})P_{dec}^d(\gamma_{sd}), \quad (28)$$

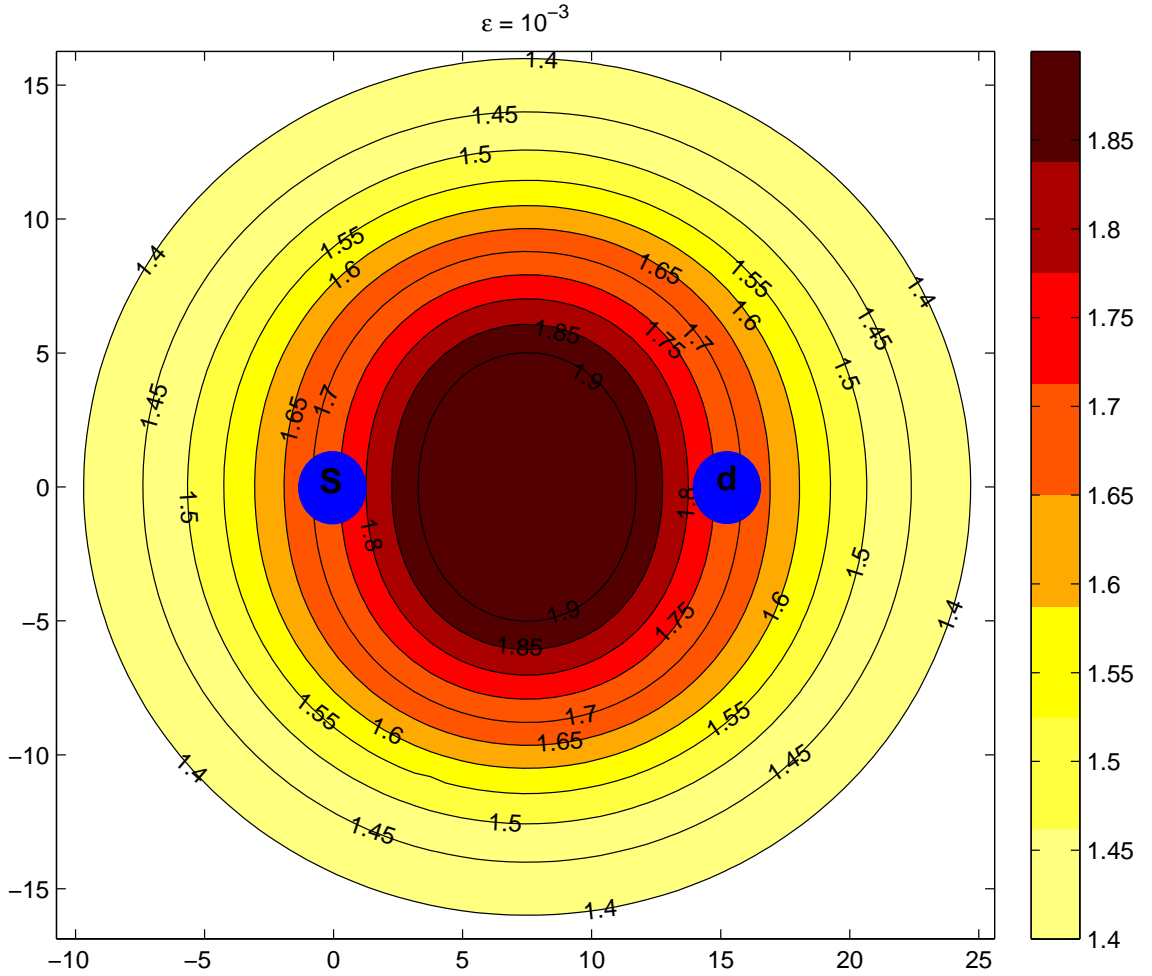


Fig. 7. Cooperation power gain of the AAF protocol over the 2-dimensional scenario for $D_{sd} = 15$ m and for a target performance constraint $\varepsilon = 10^{-3}$, using the SCBC code $C_s(3, 7)$.

where the left side is the actual power consumed by the relay for the DF protocol when the source message is unsuccessfully decoded at the relay and the right side is the actual power consumed by the relay for the SDF protocol for the same transmission case (errors at the relay). Furthermore, for this cooperative protocols category, the optimal behavior is always noted for a relay equidistant from both the source and the destination.

Moreover, from Fig. 5, we can see that for low target performance constraint (high desired frame error probability $\varepsilon = 10^{-2}$), the AF protocols category clearly outperforms the DF protocols category. For the medium regime ($\varepsilon = 10^{-3}, 10^{-4}$), the power consumption performance of both categories are quite at the same range. However, for severe target performance constraints ($\varepsilon = 10^{-5}, 10^{-6}$), the DF protocol brings the most of power savings.

In order to study the impact of the used channel code on the system power consumption performance, we plot

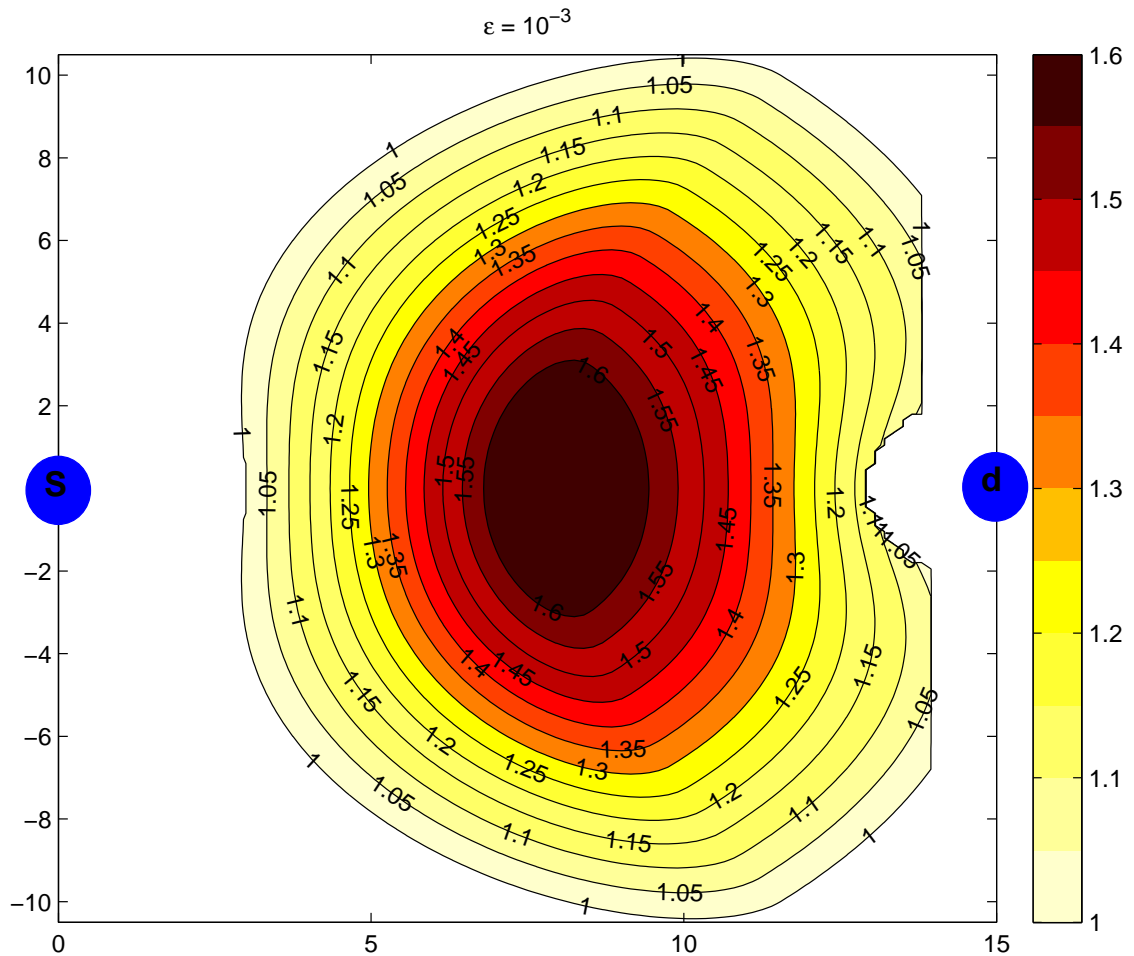


Fig. 8. Cooperation power gain of the DF protocol over the 2-dimensional scenario for $D_{sd} = 15$ m and for a target performance constraint $\varepsilon = 10^{-3}$, using the SCBC code $\mathcal{C}_s(3, 7)$.

in Fig. 6 the optimal total power consumption of cooperative protocols over the linear scenario for $D_{sd} = 15$ m, fixing the target performance constraint to 10^{-3} and using an LDPC of rate 1/2 as adopted in the 802.11ad standard. For this figure, we consider the same transmission scenario chosen for Fig. 5. From this figure, we can see that AF protocols category remains preferable to the DF protocols category since it offers more power savings. As the global behaviors and the qualitative trends of the studied protocols using the LDPC code drawn from Fig. 6 are identical to those observed from curves given based on the use of the SCBC code \mathcal{C}_s (Fig. 5 for $\varepsilon = 10^{-3}$), we can conclude that the study is quite insensitive to the employed channel code, as long as the decoding at the receiver node remains iterative. However, quantitatively, as the LDPC is known to be more efficient than the used SCBC code \mathcal{C}_s , the total power consumption is lower, regardless the cooperative protocol considered.

Finally, we consider a two-dimensional scenario where $D_{sd} = 15$ m, the source and the destination are fixed and located on a plane: s is fixed at the point $(0,0)$ m and d is fixed at the point $(15,0)$ m. For this particular setup, we give the performance of two cooperative protocols, the most power-efficient from each category, i.e., the AAF protocol and the DF protocol. The results are given with respect to a reference system, which is the non cooperative transmission, in order to show the performance improvement that is achieved by the use of AAF or DF protocol.

In Fig. 7, We give the geometrical region boundaries where the AAF protocol guarantees a minimum given cooperation power gain for a fixed source-destination distance $D_{sd} = 15$ m and a fixed target performance constraint $\varepsilon = 10^{-3}$. For instance, if the relay is located inside the contour marked by 1.4, the AAF protocol offers a cooperation power gain greater than 1.4 (exactly 1.4 on the contour). From this illustration, we note that a relay located even at the other side of the source (with $D_{rd} > D_{sd}$) can be yet beneficial for the whole cooperative system, since the received signal at the relay is appropriately amplified in order to be correctly exploited by the destination. Nevertheless, this is only valid when using omnidirectional antennas.

In Fig. 8, We give the geometrical region boundaries where the DF protocol guarantees a minimum given cooperation power gain for a fixed source-destination distance $D_{sd} = 15$ m and a fixed target performance constraint $\varepsilon = 10^{-3}$. We notice that the DF protocol is beneficial with respect to the non-cooperative case only when $D_{rd} < D_{sd}$.

Comparing now Fig. 7 and Fig. 8, it is showed that for different values of cooperation power gain, the AAF protocol offers a larger region satisfying the requested gain, when a fixed target performance constraint is adopted. This can be materialized by a better system coverage. However, results given by Fig. 7 and Fig. 8 can drastically change for different values of target frame error probability (ε).

Fig. 9 illustrates the optimal cooperative protocol as a function of both the source-destination distance (D_{sd}) and the relative relay position (d_r) for the linear scenario and for a fixed target performance constraint $\varepsilon = 10^{-3}$. The outcome of this figure is twofold: first, the AF protocols category is exclusively dominating as the optimal protocol for very short-range transmissions between the source and the destination (i.e., for $D_{sd} < 20$ m); second, for a relay located much closer to the source than to the destination ($d_r \leq 0.15$), the AF protocol is always performing the best among the studied protocols, regardless D_{sd} value. Notice that the AAF protocol can not perform worst than the AF protocol, but when the total consumed power is the same, we choose the AF protocol as the optimal one rather than the AAF protocol since it has a reduced complexity. On another hand, this figure shows that the SDF protocol can be the optimal choice for very specific and restricted conditions (D_{sd} and d_r belonging to limited ranges) compared to the other presented protocols, which is a surprising result compared with first intuitions and classical results stated for power consumption optimization when neglecting processing power. However, we notice that the longer the source-destination distance gets, the more pertinent the SDF protocol becomes; and this can be explained by the fact that the power consumed in decoding becomes less predominant.

Besides, we have to note that the choice of the channel code is not restrictive and the same analysis can be conducted for any message-passing decoder. However, for the geometrical framework, the model is no more valid for node distances below than 5 m. Furthermore, as the power consumption model is given using performance

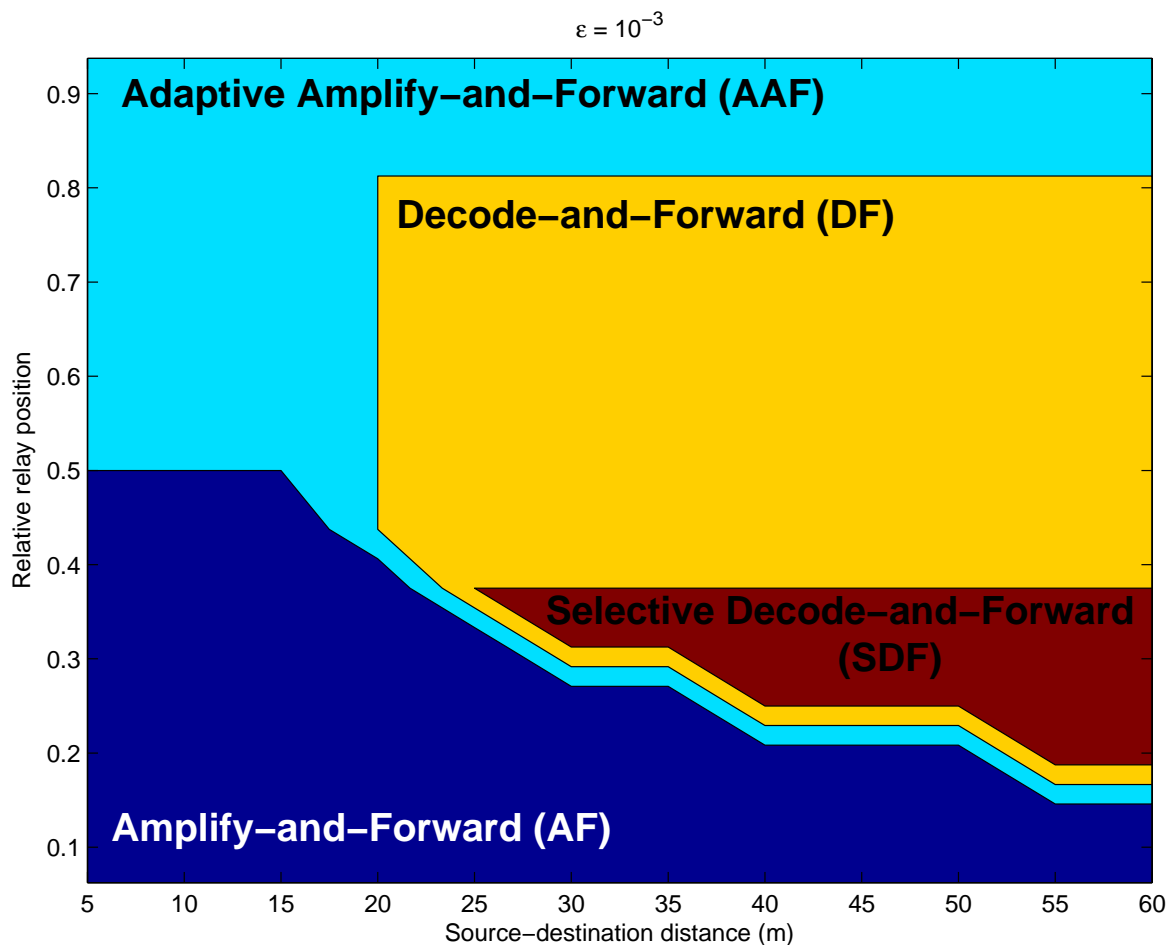


Fig. 9. Best cooperative protocol choice over the linear scenario for different values of D_{sd} and for a target performance constraint $\varepsilon = 10^{-3}$, using The SCBC code $\mathcal{C}_s(3, 7)$.

bounds, the analysis of power efficiency, even if it approaches well the reality, remains more qualitative than quantitative. Hence, it can be used to define general trends in choosing the most appropriate cooperative protocol.

V. CONCLUSIONS

Considering the decoder power consumption, this paper reconsiders the performance of well-known cooperative protocols for the single-relay channel from the power consumption perspective. The decoder consumption model considered here is specific to a message-passing decoder where the decoder implementation is abstracted as a decoder-connectivity graph. The analysis emphasizes that, even when taking into account the decoding power, cooperative transmission still offers considerable performance improvements in terms of power saving compared to the direct non-cooperative transmission. Moreover, a new classification of these cooperative protocols has been given, stating that the classical findings of studies considering only the transmission power, can not be straightforwardly

conducted for short-range transmissions, i.e., where the processing power can no more be neglected. For instance, the SDF protocol is far from being preferable to the fixed DF protocol. Furthermore, assuming locations of all nodes known, we can decide where and which cooperative protocol we have to add to increase the performance of a reference system (the direct transmission).

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