Exploiting Partial Cooperation for Source and Channel Coding in Sensor Networks

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Abstract—**A network with two sensors communicating a remote measurement to a common access point (AP) is investigated. The sensors are connected via out-of-band and finite-capacity communication links, e.g., thanks to an orthogonal radio interface, thus enabling partial cooperation. Focusing on a Gaussian model for source and observation noise and a quadratic (MSE) distortion metric, both the source coding problem (corresponding to error-free and orthogonal links to the AP), also known as the "CEO problem", and the joint source-channel coding problem over a Gaussian multiple access channel to the AP are considered. In the first case, an achievable rate-distortion trade-off is derived that generalizes known results for the CEO problem in the absence of cooperation between the sensors. For the latter case, achievable distortions are derived with separate or joint source-channel coding. Optimality of the proposed schemes is established asymptotically with the capacity of the inter-sensor links. Moreover, it is concluded that, for both scenarios, even modest values of such capacity enable the optimal performance with full cooperation to be approached.**

I. Introduction

The problem of communicating a given noisy measurement from a set of sensors to an access point (AP) for data fusion (estimation) has received considerable attention in the past few years. From an information-theoretic standpoint, the scenario falls in the category of *remote and distributed source coding* problems if the channels to the AP are orthogonal (see, e.g., [1] [2] [3]) and of *joint source-channel coding* problems in case the channel to the AP is a general multiple access channel (MAC) (see, e.g., [4] [5]). For the first case, sometimes referred to as the "CEO problem", focusing on Gaussian source and observation noises, reference [2] derived the rate-distortion region with any number of sensors, extending the earlier results in [1] where the sum-rate was derived for a symmetric scenario with homogeneous measurements. Moreover, a source-channel coding separation result was obtained in [3] that applies to sensor-AP channels that are noisy but orthogonal to each other (and not limited to be Gaussian). For the second (joint source-channel coding) case, references [4] [5] conclude that, when the bandwidth of source and channel are the same, uncoded (analog) transmission of a Gaussian source over a Gaussian MAC (GMAC) is exactly optimal.

In this work, we extend previous art in both scenarios mentioned above by enabling cooperation between the two active sensors via *inter-sensor finite-capacity noiseless links* that are orthogonal to the sensors-AP channels (out-of-band), as illustrated in Fig. 1. This assumption reasonably models the presence of a secondary radio interface (e.g., Bluetooth)

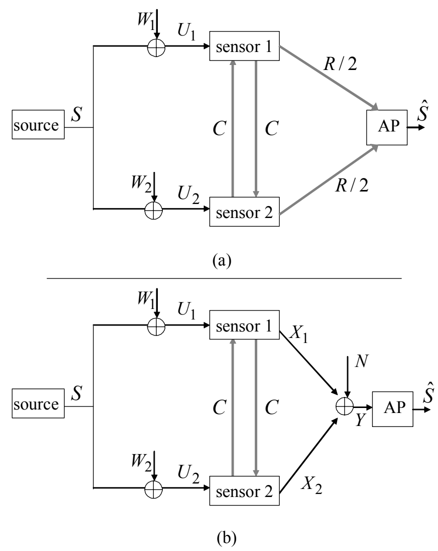

Fig. 1. Homogeneous sensor network with two active sensors cooperating via out-of-band finite-capacity links and (a) orthogonal links to the access point (AP) (CEO problem); (b) Gaussian multiple access channel (GMAC) to the AP.

that the sensor can employ to communicate between them. The analysis of cooperative techniques as enabled by finite-capacity out-of-band links was initiated by [6] and then extended in a number of works, see, e.g., [7] [8] in the context of channel coding. Distributed source coding with direct [11] [12] and remote [13] observations, and universal coding [14] has also been considered. In particular, [13] derives a lower bound on the rate-distortion function for the model in Fig. 1-(a) (CEO problem). Related works in the context of joint source-channel coding where the cooperative links are in-band (that is, in the same signal space as the sensors-AP channels) are [16] [17].

Focusing on a *symmetric (homogenous) network* as in Fig. 1, where the inter-sensor links have capacity C (bit/ source symbol), the main contributions of this paper are: (*i*) for the *CEO problem* of Fig. 1-(a), an achievable rate-distortion function is derived that reduces to the result in [1] for inter-sensor capacity $C = 0$ and is asymptotically optimal (that is, it achieves the performance with full cooperation for $C \to \infty$); (*ii*) for *joint source-channel coding over a GMAC* as in Fig. 1-(b), an asymptotically optimal scheme based on separate source and channel coding is proposed, along with an "uncoded transmission" strategy, which is also asymptotically optimal but only in the case of equal source and channel bandwidths. For both scenarios, simulation results reveal that optimality is in practice attained with small values of C. Due to space limitations, proofs are only sketched and a full treatment can be found in [19].

Notation: Vectors are denoted by bold-face characters, while the corresponding ordinary font represents the entries, as in $\mathbf{v} = [v(1) \cdots v(N)]$ (the size N of the vector will be clear from the context). Moreover, throughout the paper, all the logarithms are in base 2.

II. System Model

We consider a sensor network where at any given observation period two sensors communicate their measurements of a phenomenon, described by the discrete-time sequence $\mathbf{S} = [S(1) \cdots S(k)]$, to an AP (see Fig. 1). The "source" sequence $\mathbf{S}$ is modelled as a real white Gaussian process with $S(t) \sim \mathcal{N}(0, \sigma_S^2)$, $t = 1, ..., k$. The two sensors are such that their measurements of $\mathbf{S}$ are of the same quality:

$$U_i(t) = S(t) + W_i(t), \tag{1}$$

with $i = 1, 2$, and $W_i(t)$ being white Gaussian noise with $W_i(t) \sim \mathcal{N}(0, \sigma_W^2)$. We also assume that the number k of observed samples is large enough to allow the use of information-theoretic results. The sensors have the ability to both communicate between each other and to the AP. The overall goal of the sensors is to design transmission strategies that enable the AP to recover a "good" estimate of $\mathbf{S}$, say $\hat{\mathbf{S}}$, based on the signal received from the sensors. The quality of the reconstruction $\hat{\mathbf{S}}$ is measured by a quadratic (or mean square error, MSE) distortion: $D = \frac{1}{k}\sum_{t=1}^{k} \left| S(t) - \hat{S}(t) \right|^2$.

The sensors can communicate with each other over directional finite-capacity links of capacity C bit/ source symbol. In other words, the total number of bits that can be exchanged in each direction for observation block is kC. These links are orthogonal to each other and to the channels towards the AP. Moreover, the sensors are connected to the AP according to either one of two commonly considered models, namely *noiseless and orthogonal links* (Fig. 1-(a), see Sec. III) or *GMAC* (Fig. 1-(b), see Sec. IV).

III. Cooperative CEO Problem: Noiseless and Orthogonal Links

In this section, we address the scenario where noiseless and orthogonal links exist between the sensors and the AP (CEO problem). We are interested in characterizing the trade-off between the available rate (bit/ source symbol) on the orthogonal links to the AP, say R', and the corresponding distortion D of the reconstruction $\hat{\mathbf{S}}$, for a given inter-sensor capacity C. It is noted that, by symmetry, the two links to the AP are assumed to have equal rate R', and the results are given in terms of the sum-rate $R = 2R'$. Using conventional definitions, we will say that a given sum-rate R is achievable with distortion D, given inter-sensor capacity C, if there exists a transmission scheme, comprising inter-sensor and sensors-AP communications[1], which allows the source $\mathbf{S}$ to be reconstructed with distortion smaller or equal to D.

A. Reference Results

Here we establish reference results corresponding to the rate-distortion trade-off in the absence of cooperation ($C = 0$) or full cooperation ($C \to \infty$). These results clearly set, respectively, an upper and a lower bound on the smallest achievable sum-rate R for a given distortion D in the presence of finite-capacity links between the sensors ($0 < C < \infty$).

Proposition 1 [1]. The rate-distortion function with no cooperation (NC) is given by

$$R_{NC}(D) = \frac{1}{2}\log^+\left(\sigma_S^2(\mu^2\sigma_W^2 + 1)^2\left(\frac{1}{\sigma_S^2} + \frac{2\mu^2}{\mu^2\sigma_W^2 + 1}\right)\right) \tag{2}$$

for μ such that $\frac{1}{D} = \frac{1}{\sigma_S^2} + \frac{2}{\sigma_W^2 + \frac{1}{\mu^2}}$. Moreover, in the presence of full cooperation (FC) ($C \to \infty$), the rate-distortion function is:

$$R_{FC}(D) = \frac{1}{2}\log^+\left(\frac{\sigma_S^2 - D_0}{D - D_0}\right) \tag{3}$$

with

$$D_0 = \frac{1}{\frac{1}{\sigma_S^2} + \frac{2}{\sigma_W^2}}. \tag{4}$$

Remark 1: The rate-distortion $R_{FC}(D)$ with FC is easily obtained by considering that, in the presence of FC, the two sensors share both measurements $\mathbf{U}_1$ and $\mathbf{U}_2$, and thus can be considered as a single transmitter. It follows that the model can be studied as a point-to-point system with remote observations, for which the rate-distortion function is well known. We also notice that D_0 in (4) is the distortion that could be achieved if the AP had direct access to the two sequences of measurements $\mathbf{U}_1$ and $\mathbf{U}_2$, that is $D_0 = E[(S - E[S|U_1U_2])^2]$, and is thus a lower bound on the achievable distortion for *any* transmission strategy, including cooperation: $D > D_o$.

B. Achievable Rate-Distortion Function With Partially Cooperating Sensors

The following proposition defines an achievable rate for the scenario at hand of partially cooperating sensors.

Proposition 2. Let us define the parameter

$$\sigma_Q^2(C) = \frac{\sigma_W^2}{2^{2C} - 1}\left(\frac{2 + \sigma_W^2/\sigma_S^2}{1 + \sigma_W^2/\sigma_S^2}\right). \tag{5}$$

The following sum-rate is achievable with distortion D and inter-sensor capacity C

$$R_C(D, C) = \frac{1}{2}\log^+\left(\sigma_S^2\left(\mu^2\mathcal{K}^2 + 1\right)^2\left(\frac{1}{\sigma_S^2} + \frac{2\mu^2}{\mu^2\mathcal{K}^2 + 1} - \frac{\mu^4\mathcal{P}(\mathcal{P} + 2\sigma_S^2)}{\sigma_S^2\left(\mu^2\mathcal{K}^2 + 1\right)^2}\right)\right), \tag{6}$$

[1] We use standard definitions for available transmission strategies, see, e.g., [6] for a rigorous statement.

with definitions

$$\mathcal{K}^2(C) = \frac{(1+a^2)}{(1+a)^2}\sigma_W^2 + \frac{a^2}{(1+a)^2}\sigma_Q^2(C) \quad (7a)$$

$$\mathcal{P} = \frac{2a\sigma_W^2}{(1+a)^2} \quad (7b)$$

for any a and μ that satisfy

$$\frac{1}{D} = \frac{1}{\sigma_S^2} + \frac{2}{\sigma_W^2 + \frac{1}{\mu^2} + \frac{a^2}{(1+a)^2}\sigma_Q^2(C)}. \quad (8)$$

Remark 2: The achievable rate (6) is easily shown to reduce to the upper bound (2) for $C \to 0$ (by setting $a = 0$ in (6)) and to the lower bound (3) for $C \to \infty$.

Remark 3: A lower bound on the achievable rate (6) was calculated in [13] for a more general observation model (1) with unequal noise powers. As discussed in [19], this bound is quite loose for the scenario at hand here.

Sketch of proof of Proposition 2: As detailed in the full proof in [19], the achievable rate (6) is obtained with the following transmission scheme. Each jth sensor ($j = 1, 2$) compresses the local measurement $\mathbf{U}_j$ via a Gaussian quantization codebook using C bit/ source symbol. The quantized codeword $\hat{\mathbf{U}}_j$ is then sent by the jth sensor to the other sensor (say the ith) via the corresponding finite-capacity link using Wyner-Ziv compression. This compression exploits the fact that the ith sensor has side information about $\mathbf{U}_j$, having available the correlated sequence $\mathbf{U}_i$ [18]. Based on the local measurement $\mathbf{U}_i$ and the signal received from the other sensor $\hat{\mathbf{U}}_j$, the ith sensor reconstructs a local estimate $\mathbf{U}_i' = \mathbf{U}_i + a\hat{\mathbf{U}}_j$, where a is a parameter. The local estimates $\mathbf{U}_i'$, $i = 1, 2$, are then compressed at the two sensors using the Berger-Tung coding scheme, which essentially amounts to vector quantization followed by random binning (see [1] and [19]). The AP finally reconstruct an estimate $\hat{\mathbf{S}}$ via a Minimum MSE (MMSE) estimate based on the signals received from the sensors. As a final remark, it is noted that the sensors could in principle exchange multiple messages over the inter-sensor links in an interactive fashion. However, with Gaussian measurements, it is known that there are no further rate gains that can be achieved in compressing any sequence $\mathbf{U}_j$ by exploiting some information at the encoder about the correlated sequence $\mathbf{U}_i$ available at the decoder: in the Gaussian case, compression with and without side information at the transmitter have the same efficiency [18] [10].

Remark 4: The sketch of the proof above suggests that choosing parameter a such that the local estimate $\mathbf{U}_i'$ is a (scaled) MMSE estimate of $\mathbf{S}$, that is $a_M = \left(1 + \sigma_Q^2(C)/\sigma_W^2\right)^{-1}$ could be a good design choice for minimizing $R_C(D, C)$ (6) (Notice that, once a is fixed, μ needs to be selected so as to satisfy (8)). However, the optimality of $a = a_M$ is not a priori obvious, since a MMSE estimate $\mathbf{U}_i'$ would improve the local SNR but not necessarily the overall compression efficiency, due to the correlation of the equivalent observation noises in the local estimates $\mathbf{U}_1'$ and $\mathbf{U}_2'$. It is clear that $a = a_M$ is the optimal choice for $C \to \infty$ since in this case, by symmetry, $a = 1$ is optimal. In [19] it is shown via numerical simulations that, in practice, $a = a_M$ is optimal for inter-sensor capacity C large enough.

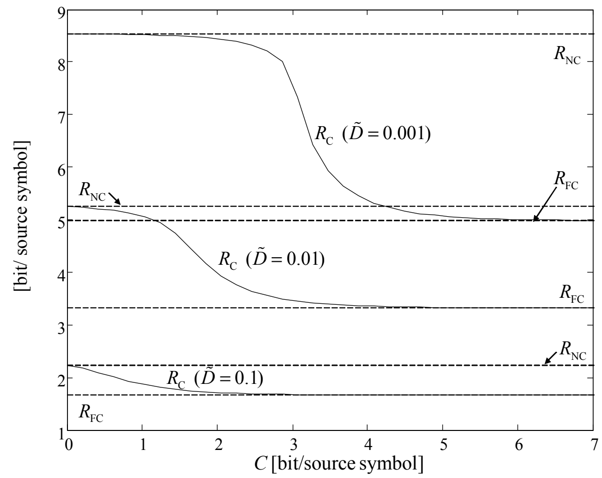

Fig. 2. Achievable rate $R_C(D, C)$ (6) with optimal a, along with the upper bound (no cooperation) $R_{NC}(D)$ (2) and the lower bound (full cooperation) $R_{FC}(D)$ (3), versus C for $\tilde{D} = 0.1$, 0.01 and 0.001, $\sigma_S^2/\sigma_W^2 = 5$dB.

C. Numerical Results

Here we provide some insight into the properties of the achievable rate $R_C(D, C)$ (6), as compared to the upper bound (no cooperation) $R_{NC}(D)$ (2) and the lower bound (full cooperation) $R_{FC}(D)$ (3). It is convenient to measure the distortion D as the excess distortion with respect to the minimum distortion D_o (4), $(D - D_o)$, normalized over the maximum excess distortion $(\sigma_S^2 - D_o)$, as $\tilde{D} = (D - D_o)/(\sigma_S^2 - D_o)$. Fig. 2 shows the achievable rates with optimal a evaluated numerically for $R_C(D, C)$ (6). It can be seen that, as predicted by the analysis, as the capacity C increases, the achievable rate $R_C(D, C)$ decreases from the upper $(R_{NC}(D))$ to the lower $(R_{FC}(D))$ bound. It is interesting to notice that even a relatively small capacity is enough for the achievable rate to approach the performance of full cooperation $R_{FC}(D)$ (3). Moreover, smaller distortion values call for larger capacities C: for instance, for normalized distortion $\tilde{D} = 0.01$, $C \simeq 5$ is enough, while reducing the normalized distortion by an order of magnitude ($\tilde{D} = 0.001$) requires $C \simeq 7$.

IV. Cooperative Source-Channel Coding

In this section, we turn to the investigation of the system in Fig. 1-(b), where communications between sensors and AP occur over a GMAC. Accordingly, the signal received at the AP for each channel symbol is $Y(s) = X_1(s) + X_2(s) + N(s)$, with $s = 1, ..., n$, where $X_i(s)$ are the channel symbols transmitted by the ith sensor and $N(s)$ is additive white Gaussian noise with $N(s) \sim \mathcal{N}(0, \sigma_N^2)$. The average power constraint for each sensor is given by $P_{tot}/2$ as $E[X_i^2] \le P_{tot}/2$, so that the total power available (per channel symbol) is P_{tot}. Finally, we define the ratio between the number of channel and source samples per observation block as $b = n/k$, which can be also interpreted as the *bandwidth ratio* (between channel and source bandwidths). We are interested in obtaining achievable distortions D given a channel SNR P_{tot}/σ_N^2 and an inter-sensor capacity C (measured, as in the previous section, in bit/ source symbol).

A. Lower Bound on the Achievable Distortion

We first set a lower bound on the achievable distortion D following [5].

Proposition 3 [5]. A lower bound on the achievable distortion for the system in Fig. 1-(b) is given by:

$$D_{FC}(P_{tot}) = D_o + \frac{\sigma_S^2 - D_o}{\left(\frac{2P_{tot}}{\sigma_N^2} + 1\right)^b}. \tag{9}$$

Remark 5: As detailed in [5], this bound follows immediately by cut-set arguments, that is, by assuming full cooperation (FC) between the two sensors. In fact, with FC, the system can be studied as a point-to-point link and thus the source-channel coding separation theorem applies. Distortion (9) is then achieved by setting $R_{FC}(D) = b \cdot r_{FC}(P_{tot})$, where

$$r_{FC}(P_{tot}) = \frac{1}{2}\log\left(1 + \frac{2P_{tot}}{\sigma_N^2}\right) \tag{10}$$

is the sum-capacity on the GMAC with FC (measured in bit/ channel symbol). It is also noted that bound (9) holds also in the presence of feedback from the AP since feedback does not improve capacity of point-to-point links [5].

B. Separate Source-Channel Coding

Here we consider a transmission strategy based on a separation approach, whereby compression (source coding) and channel coding are performed separately. It is recalled that the source-channel coding separation theorem, unlike point-to-point models, does not hold in general multiuser scenarios, so that a separation-based approach is generally suboptimal. We allow the inter-sensor capacity C to be used for a fraction of time γ to facilitate source coding and for the remaining fraction $1-\gamma$ to enable cooperative channel coding.

Proposition 4. The distortion $D_{SCC}(P_{tot}, C)$ achievable with separate cooperative source and channel coding (SCC) is obtained by solving the following equation for a given $0 < \gamma < 1$:

$$R_C(D_{SCC}, \gamma C) = r_{CC}(P_{tot}, (1-\gamma)C), \tag{11}$$

with

$$r_{CC}(P_{tot}, C) = \begin{cases} \frac{1}{2}\log\left(\left(1 + \frac{P_{tot}}{\sigma_N^2}\right)\frac{2}{1+2^{-2C/b}}\right) & 0 \le C < C_o \\ r_{FC}(P_{tot}) & C \ge C_o \end{cases} \tag{12}$$

and $C_o = \frac{b}{2} r_{FC}(P_{tot})$, where $R_C(D, C)$ in (6) is evaluated for a given value of parameter a.

Proof: The transmission scheme is based on separate source-channel coding, where source coding is performed as discussed in Sec. III and cooperative channel coding takes place following the approach of [6]. See [19] for full proof.

Remark 6: For $C \to \infty$ and any $0 < \gamma < 1$, the SCC scheme is optimal, that is, $D_{SCC}(P_{tot}, C)$ tends to the lower bound (9): $D_{SCC}(P_{tot}, C) \to D_{FC}(P_{tot})$. In fact, in this case, we have $R_C(D, C) \to R_{FC}(D)$ (see Sec. III) and $r_{CC}(P_{tot}, C) \to r_{FC}(P_{tot})$. In essence, in such scenario, the two sensors can be considered as a single transmitter with measurements $\mathbf{U}_1$ and $\mathbf{U}_2$ and power constraint $2P_{tot}$, and thus, applying source-channel coding separation theorem, distortion (9) is achievable (see Remark 5).

C. Joint Source-Channel Coding: Uncoded Transmission

We now turn to a simple joint source-channel coding approach, which generalizes the uncoded transmission strategy that has been shown in [5] to be exactly optimal for the non-cooperative case ($C = 0$) and $b = 1$. The latter condition will be assumed throughout this section, while for the case $b > 1$ some brief considerations are provided in [19]. According to the uncoded (or analog) strategy, the two sensors at first exchange compressed versions of their measurements via the inter-sensor links as in the strategy outlined in Sec. III-B and then simply amplify-and-forward the updated local measurements $\mathbf{U}'_i$ (see Sec. III-B) to the AP. The latter finally reconstructs the source $\mathbf{S}$ via MMSE estimation.

Proposition 5. The following distortion is achievable with uncoded transmission (UT) and $b = 1$:

$$D_{UT}(P_{tot}, C) = \frac{1}{\frac{1}{\sigma_S^2} + \frac{4(1+a)^2}{2(1+a)^2\sigma_W^2 + 2a^2\sigma_Q^2(C) + \sigma_N^2/G^2}} \tag{13}$$

with $\sigma_Q^2(C)$ in (5),

$$G^2 = \frac{P_{tot}/2}{(1+a^2)\sigma_W^2 + (1+a)^2\sigma_S^2 + a^2\sigma_Q^2(C)} \tag{14}$$

and any a.

Proof: See [19]

Remark 7: The distortion (13) generalizes the result in [4] [5], which is obtained for $a = 0$.

Remark 8: Selection of the optimal a (i.e., minimizing the distortion) for the uncoded (UT) scheme considered here and the SC and SCC schemes discussed above follow the general comments provided in Sec. III. In particular, the MMSE choice $a = a_M$ (see Remark 4) is clearly optimal for $C \to \infty$ and can be seen by numerical results to be optimal also for moderate C.

Remark 9: It can be shown with some algebra that the distortion (13) tends to the lower bound (9) corresponding to FC for $C \to \infty$ and $b = 1$ (by setting $a = 1$). It follows that for very large C and $b = 1$, one can either use the separation-based approach SCC of Proposition 4 or the simpler uncoded scheme considered here and achieve minimum distortion D_{FC}. As recalled above, from [5], we know that uncoded transmission is also optimal for $C = 0$ and $b = 1$. Notice that this result is shown in [5] using a different lower bound than (9), which does not appears to be easily extended to the scenario at hand for any value of C.

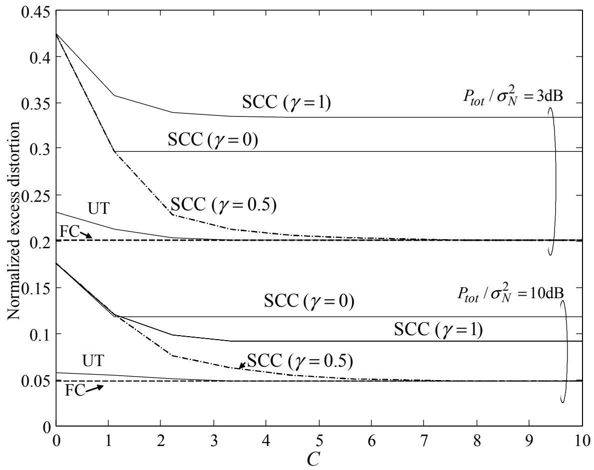

Fig. 3. Achievable normalized excess distortions $(D - D_o)/(\sigma_S^2 - D_o)$ for separate source-channel coding D_{SCC} (11) and uncoded transmission D_{UT} (13), along with the lower bound D_{FC} (9), versus the inter-sensor capacity C for $b = 1$ and $P_{tot}/\sigma_N^2 = 3\text{dB}$ and 10dB.

D. Numerical results

In this section, we report some numerical results that corroborate the analysis of the previous sections for the model of Fig. 1-(b). As in the previous section, we measure the achievable distortions D as the normalized excess distortion $\tilde{D} = (D - D_o)/(\sigma_S^2 - D_o)$. Fig. 3 shows such achievable distortions for cooperative source and channel coding D_{SCC} (11) with different values of γ and uncoded transmission D_{UT} (13), along with the lower bound D_{FC} (9) versus the inter-sensor capacity C for $b = 1$, $\sigma_S^2/\sigma_W^2 = 3\text{dB}$ and $P_{tot}/\sigma_N^2 = 3\text{dB}$ and 10dB. We remark that parameter a has been optimized numerically, and similar conclusions have been drawn as in Sec. III (not shown). From Fig. 3, it is seen that, as predicted by the analysis, UT and SCC are both optimal (i.e., they attain the lower bound) for C large enough. It is interesting to notice that, as for the case of orthogonal links of Fig. 1-(a) studied in Sec. III, a relatively small capacity (here $C \simeq 3$ for UT) is sufficient to achieve the lower bound, and that in general SCC requires a larger capacity C than UT. Moreover, we see that using only cooperative channel coding, i.e., $\gamma = 0$, generally performs better than using only cooperative source coding ($\gamma = 1$) for low channel SNR P_{tot}/σ_N^2 where improving the link quality via cooperation is crucial, whereas the opposite is true if the channel SNR is large enough.

V. Conclusions

The availability of out-of-band finite-capacity channels for signalling between encoders or decoders has been previously shown to be an effective means to enable cooperative transmission/ reception techniques. In this paper, we have extended such considerations to the case of remote and distributed source coding with two encoders (sensors) in a small sensor network (CEO problem). Transmission techniques that achieve the optimal performance of full cooperation with modest values of the inter-sensor capacity have been proposed for both orthogonal and noiseless channels to the AP and the corresponding joint source-channel coding problem over a Gaussian MAC. The analysis is limited to a symmetric scenario with homogeneous sensors. Further work is need to characterize optimal transmission strategies for finite-value of the inter-sensor capacity and extend the results to asymmetric scenarios.

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