Energy-Distortion Tradeoff for the Gaussian Broadcast Channel with Feedback

Yonathan Murin\(^1\), Yonatan Kaspi\(^2\), Ron Dabora\(^3\), and Deniz Gündüz\(^4\)

\(^1\)Stanford University, USA, \(^2\)University of California, San Diego, USA, \(^3\)Ben-Gurion University, Israel, \(^4\)Imperial College London, UK

Abstract—This work focuses on the minimum transmission energy required for communicating a pair of correlated Gaussian sources over a two-user Gaussian broadcast channel with noiseless and causal channel output feedback (GBCF). We study the fundamental limit on the required transmission energy for broadcasting a pair of source samples, such that each source can be reconstructed at its respective receiver to within a target distortion, when the source-channel bandwidth ratio is not restricted. We derive a lower bound and three distinct upper bounds on the minimum required energy. For the upper bounds we analyze three transmission schemes: Two schemes are based on separate source-channel coding, and apply coding over multiple samples of source pairs. The third scheme is based on joint source-channel coding obtained by extending the Ozarow-Leung (OL) transmission scheme, which applies uncoded linear transmission. Numerical simulations show that despite its simplicity, the energy-distortion tradeoff of the OL-based scheme is close to that of the better separation-based scheme, which indicates that the OL scheme is attractive for energy-efficient source transmission over GBCFs.

I. INTRODUCTION

We study the energy-distortion tradeoff (EDT) for the transmission of a correlated pair of Gaussian sources over a two-user Gaussian broadcast channel (GBC) with noiseless causal feedback, referred to as the GBCF. EDT, recently proposed for the multiple-access channel (MAC) and the point-to-point channel in \([1]\), characterizes the minimum energy-per-source sample required to achieve a target distortion pair at the receivers, without constraining the source-channel bandwidth ratio. In many practical scenarios, e.g., satellite broadcasting \([2]\), sensor networks measuring physical processes \([3]\), and in particular wireless body-area sensor networks \([4]\), an extremely high energy efficiency is required for broadcasting correlated observations, while the available power is limited. It follows that there is a strong motivation for studying the EDT for broadcasting correlated sources, and in the present work we focus on EDT for feedback-assisted scenarios, represented by the GBCF.

It is well known that, for lossy source transmission over memoryless Gaussian point-to-channel channels, with or without feedback, when the bandwidth ratio is fixed and the average power per channel use is limited, separate source and channel coding (SSCC) achieves the minimum possible average distortion \([5]\) Thm. 3. In \([1]\) Cor. 1 it is further shown that SSCC is optimal in the EDT sense as well: For any target distortion level, the minimal transmission energy is achieved by optimal lossy compression followed by the most energy efficient channel coding.

In contrast to the point-to-point setting, in multi-user scenarios joint design of the source and channel codes can improve the performance \([6]\). However, we have a relatively limited understanding of the impact of feedback on joint source-channel coding (JSCC) over multi-user channels. The work \([7]\) presented several achievability schemes and a set of necessary conditions for losslessly transmitting a pair of discrete and memoryless correlated sources over a MAC with feedback. Lossy transmission of correlated Gaussian sources over a two-user Gaussian MAC with feedback was studied in \([8]\), in which sufficient conditions as well as necessary conditions for the achievability of a mean square error (MSE) distortion pair were derived. While \([8]\) considered only source-channel coding with a unit bandwidth ratio, \([1]\) studied the EDT for the transmission of correlated Gaussian sources over a two-user Gaussian MAC with and without feedback, when the bandwidth ratio is not restricted.

Previous works on GBCFs mainly studied the channel coding aspects which applies to independent and uniformly distributed messages \([9]-[11]\). JSCC of correlated Gaussian sources over GBCFs was also studied in \([12]\), in which the minimal number of channel uses required to achieve a target MSE distortion pair was characterized for three linear encoding schemes, using uncoded transmission: The first scheme is a JSCC scheme based on the coding scheme of Ozarow and Leung \([9]\), to which we shall refer as the OL scheme; the second scheme is a JSCC scheme based on the linear quadratic Gaussian (LQG) coding scheme of \([11]\), to which we shall refer as the LQG scheme; and the third scheme is a JSCC scheme whose parameters are obtained using dynamic programming (DP).\(^1\) We note that the advantages of linear and uncoded transmission, as implemented in the OL and LQG schemes, include a low computational complexity, low coding delays, and low storage requirements. In the present work we analyze lossy source coding over GBCFs using SSCC and JSCC broadcasting schemes based on a different performance metric – the EDT.

Main Contributions: This is the first work towards characterizing the EDT in GBCFs. We derive lower and upper bounds on the minimum energy required to achieve a target MSE distortion pair when transmitting a pair of Gaussian sources over a two-user GBCF, without constraining the number of channel uses per source sample. The proposed lower bound is based on cut-set arguments, and the upper bounds are obtained

\(^1\)In the present work we discuss only the former two schemes, since the scheme based on DP becomes analytically and computationally untractable as the number of channel uses goes to infinity.

This work was supported by Israel Science Foundation under grant 396/11.
using three transmission schemes: Two SSCC schemes and an uncoded JSCC scheme. The first SSCC scheme \textit{jointly} compresses the two source sequences into a single bit stream, and transmits this stream using a channel code, designed for the transmission of a common message. The second SSCC scheme \textit{separately} encodes each source sequence into two distinct bit streams, and then transmits the resulting two bit streams via the LQG channel code of (11). It is shown that, in terms of the minimum energy per bit, the LQG code provides no gain compared to orthogonal transmission, from which we conclude that the first SSCC scheme, which jointly compresses the sequences into a single stream, is more energy efficient. As both SSCC schemes apply coding over multiple samples of the source pairs, they require a high computational complexity, long delays, and large storage. Thus, motivated by the low computational complexity, short coding delay, and small storage requirements of the uncoded OL scheme presented in (12), we use this scheme to obtain a third upper bound on the EDT.

Numerical results indicate that the SSCC scheme based on joint compression achieves a better EDT compared to the JSCC OL scheme; yet, in many scenarios the gap is quite small. Moreover, in many applications there is a constraint on the maximal allowed latency. In such scenarios, coding over large blocks of independent and identically distributed (i.i.d.) pairs of source samples introduces unacceptable delays, and instantaneous transmission of each observed pair of source samples via the proposed JSCC-OL scheme may be preferable in order to satisfy the latency requirement, while maintaining high energy efficiency.

The rest of this paper is organized as follows: The problem formulation is detailed in Section II. Bounds on the minimum energy are derived in Section III. Numerical results are described in Section IV and concluding remarks are provided in Section V.

\textbf{Notation}: We use capital letters to denote random variables, e.g., $X$, and boldface letters to denote column random vectors, e.g., $\mathbf{X}$, where the $k$-th element of a vector $\mathbf{X}$ is denoted by $X_k, k \geq 1$. We use sans-serif fonts to denote matrices, e.g., $\mathbf{Q}$. Finally, we use $E \{ \cdot \}$, $(\cdot)^T$, $\log(\cdot)$, and $\mathcal{R}$ to denote stochastic expectation, transpose, natural basis logarithm, and the set of real numbers, respectively.

\section{Problem Definition}

Fig. 1 depicts the two-user GBFC, in which all the signals are real. The encoder observes $m$ i.i.d. realizations of a correlated and jointly Gaussian pair of sources $(S_{1,j}, S_{2,j}) \sim \mathcal{N}(0, Q_j), j = 1, \ldots, m$, where $Q_j \triangleq \sigma_1^2 \cdot \begin{bmatrix} 1 & \rho_s \\ \rho_s & 1 \end{bmatrix}, |\rho_s| < 1$. Both sources generate their realizations at a fixed rate. The task of the encoder is to send the observations of the $i$-th source $S_{i,1}^m; i=1,2$, to the $i$-th decoder (receiver) denoted by $R_{x_i}$. The received signal at time $k$ at $R_{x_i}$ is given by:

$$Y_{i,k} = X_k + Z_{i,k}, \quad i = 1, 2,$$

for $k = 1, \ldots, n$, where the noise sequences $(Z_{1,k}, Z_{2,k})_{k=1}^n$ are i.i.d. over $k = 1, 2, \ldots, n$, with $(Z_{1,k}, Z_{2,k}) \sim \mathcal{N}(0, Q_2)$, where $Q_2 \triangleq \sigma_2^2 \cdot \begin{bmatrix} 1 & \rho_2 \\ \rho_2 & 1 \end{bmatrix}, |\rho_2| < 1$. Let $Y_{k} \triangleq (Y_{1,k}, Y_{2,k})$. $R_{x_1}, R_{x_2}$, i = 1, 2, uses its channel output sequence $Y_{i,n}^m$ to estimate $S_{i,1}^m$ via $S_{i,1}^m = g_i(Y_{i,n}^m), g_i: \mathcal{R}^m \rightarrow \mathcal{R}^m$. The encoder maps the observed pair of source sequences and the noiseless causal channel outputs obtained through the feedback links into a channel input via: $X_k = f_k(S_{1,k}^m, S_{2,k}^m, Y_1, Y_2, \ldots, Y_{k-1}), f_k : \mathcal{R}^{2(m+k-1)} \rightarrow \mathcal{R}$.

We study the symmetricGBFC with parameters $(\sigma_1^2, \rho_s, \sigma_2^2, \rho_2)$, and define a $(D, E, m, n)$ code to be a collection of $n$ encoding functions $\{f_k\}_{k=1}^n$ and two decoding functions $g_1, g_2$, that satisfy the MSE distortion constraint:

$$\sum_{j=1}^m E \{(S_{i,j} - \hat{S}_{i,j})^2\} \leq mD, \quad 0 < D \leq \sigma_1^2, \quad i = 1, 2, (2)$$

and energy constraint:

$$\sum_{k=1}^n E \{X_k^2\} \leq mE. \quad (3)$$

Constraint (3) reflects the energy per source sample rather than per channel use. Note that defining $P \triangleq nE$, constraint (3) can be equivalently stated as $\frac{1}{n} \sum_{k=1}^n E \{X_k^2\} \leq P$, which is the well known average power constraint. Our objective is to characterize the minimal $E$, for a given target MSE $D$ at each user, such that for all $\epsilon > 0$ there exists $m, n$ and a $(D, \epsilon, E + \epsilon, m, n)$ code. We call this minimal value the EDT, and denote it by $E(D)$. In the next section we present lower and upper bounds on $E(D)$.

\section{Bounds on $E(D)$}

\subsection{A. Lower Bound on $E(D)$}

Our first result is a lower bound on $E(D)$. We begin with defining the following rate-distortion functions, see [14, Sec. III.B]:

$$R_S(D) \triangleq \frac{1}{2} \log_2 \left( \frac{\sigma_1^2}{D} \right), \quad (a)$$

$$R_{S_1, S_2}(D) \triangleq \left\{ \begin{array}{ll} \frac{1}{2} \log_2 \left( \frac{\sigma_2^2(1+|\rho_1|)}{D\sigma_1^2(1-|\rho_1|)} \right), & D > \sigma_1^2(1-|\rho_1|) \\ \frac{1}{2} \log_2 \left( \frac{\sigma_1^2(1-|\rho_1|)}{D\sigma_2^2} \right), & D \leq \sigma_1^2(1-|\rho_1|). \end{array} \right. \quad (b)$$

Note that $R_S(D)$ is the rate-distortion function for the source variable $S_1$, while $R_{S_1, S_2}(D)$ is the rate distortion function for jointly compressing the pair of sources $(S_1, S_2)$ into a single stream of rate $R \geq R_{S_1, S_2}(D)$. Note that [14, Sec. III.B] uses the function $R_{S_1, S_2}(D_1, D_2)$ as it considers a different distortion constraint for each source. For the present case, in which the same distortion constraint is applied to both sources, $R_{S_1, S_2}(D)$ can be obtained by setting $D_1 = D_2 = D$ in [14].
Eq. (10), and thus we use the simplified notation $R_{S_1, S_2}(D)$. The lower bound on $E(D)$ is stated in the following theorem: Theorem 1. The EDT $E(D)$ satisfies $E(D) \geq E_{lb}(D)$, where:

$$E_{lb}(D) = \sigma_e^2 \cdot \log_2 2 \cdot \max \{ 2R_{S_1}(D), (1+\rho_2)R_{S_1, S_2}(D) \}.$$

(5)

Proof Outline: Consider a symmetric setting, we can focus on the distortion at Rx1. To obtain (5), we derive two different lower bounds. The first bound is derived by ignoring Rx2 and requiring that the distortion at Rx1 will be $D$. The second bound is obtained by considering the transmission of both sources over a point-to-point channel with two outputs $Y_1$ and $Y_2$. In [13, Sec. III] we explicitly compute the resulting lower bounds. Theorem 1 states that $E_{LB}(D)$ is used for the lower bound. Theorem 1 is further supported in [14, Thm. III.1] (note that this code does not need the causal feedback $D_{lb}$). Let $E_{lb}(D)$ denote the minimum energy-per-bit required for reliable transmission over the Gaussian point-to-point channel $E_{lb}(D)$. From [16, pg. 1025] we have $E_{lb}(D) = 2\sigma_e^2 \log_2 2$. As the considered scheme is based on source-channel separation, the achievable EDT is given by $E(D) = E_{lb}(D) \times R_{S_1, S_2}(D)$, where $R_{S_1, S_2}(D)$ is stated in [4b]. This results in the EDT in (6).

2) The SSCC-$\rho_z$ Scheme (Utilizing $\rho_z$): This scheme utilizes the correlation among the noise components, which is available through the feedback links for channel encoding, but does not use the correlation between the sources in the compression. First, each of the source sequences is encoded using the optimal rate-distortion source code for scalar Gaussian sources [15, Thm. 13.3.2]. Then, the resulting two bit streams are sent over the GBCF using the LQG channel coding scheme of [11]. The following theorem characterizes the minimum energy per source sample required by this scheme:

Theorem 3. The SSCC-$\rho_z$ scheme achieves the EDT:

$$E_{sep}(\rho_z)(D) = 2\sigma_e^2 \log_2 \epsilon$$

Proof: The encoder separately compresses each source sequence at rate $R_{S_i}(D)$, where $R_{S_i}(D)$ is given in [4b]. Thus, from each encoded stream the corresponding source sequence can be recovered to within a distortion $D$. Then, the two encoded bit streams are transmitted to both receivers using the LQG channel coding scheme of [11]. Theorem 3 also characterizes the minimum energy per pair of encoded bits, required by the LQG scheme. In [13, Appendix, B] we show that for the symmetric scenario $E_{LQG}(D) = 2\sigma_e^2 \log_2 2$. Since two bit streams are transmitted, the achievable EDT is given by $E(D) = E_{LQG}(D)$, yielding $E_{sep}(\rho_z)(D) = 2\sigma_e^2 \log_2 \epsilon$. Theorem 3 is further supported in [15, Thm. 10.1.1] (note that this code does not need the causal feedback $D_{lb}$).

Remark 1. Since $E_{sep}(\rho_z)(D)$ is independent of $\rho_z$, the LQG scheme cannot take advantage of the correlation among the noise components to improve the minimum energy per source sample needed in the symmetric setting. Indeed, an EDT of $E_{sep}(\rho_z)(D)$ can also be achieved by transmitting the two bit streams via time sharing over the GBCF without using the feedback.

Remark 2. We observe that $E_{sep}(\rho_z)(D) \leq E_{sep}(\rho_z)(D)$ for $D \leq \sigma_e^2 (1-|\rho_z|)$ this relationship directly follows from the expressions of $E_{sep}(\rho_z)(D)$ and $E_{sep}(\rho_z)(D)$. For $D > \sigma_e^2 (1-|\rho_z|)$ the above relationship holds if the polynomial $q(D) = D^2(1+|\rho_z|) - 2\sigma_e^2 D + \sigma_e^2 (1-|\rho_z|)$ is positive. This is satisfied as the discriminant of $q(D)$ is negative. We thus conclude that it is preferable to use the correlation between the sources than the correlation between the noise components.

C. An Upper Bound on $E(D)$ via JSSC

Next, we derive an upper bound on $E(D)$ using the uncoded JSSC OL scheme. This scheme sequentially transmits the source pairs $(S_{1,j}, S_{2,j}), j = 1, 2, \ldots, m$, without applying a source code. We note that the OL scheme is designed...
for a fixed $P = \frac{E}{\rho}$, and from condition (3) we obtain that $P = \frac{E}{\rho} \geq \frac{1}{2} \sum_{n=1}^{K} \mathbb{E} \{ X_n^2 \}$. An upper bound on $E(D)$ is obtained by calculating the minimal number of channel uses required by the OL scheme to achieve the target distortion $D$, denoted by $K_{OL}(P, D)$, and then obtaining the required energy via $\sum_{K=1}^{K_{OL}(P, D)} \mathbb{E} \{ X_K^2 \}$.

In the OL scheme, each receiver recursively estimates its intended source. Using the feedback, the transmitter tracks the estimation errors at the receivers, and sends a linear combination of these errors, where the scheme is terminated after $K_{OL}(P, D)$ channel uses. For a detailed description of the proposed OL-based JSCC scheme we refer the reader to [13, Sec. VA]. Let $E_{OL-min}(D)$ denote the minimal energy per source-pair sample, required to achieve an MSE of $D$ using the JSCC OL scheme. The following theorem presents an upper bound on $E_{OL-min}(D)$, and therefore on $E(D)$.

**Theorem 4.** Let $D_{th} \triangleq \frac{\sigma_1^2(2-\rho_z-|\rho_s|)}{2-\rho_z}$, Then, $E_{OL-min}(D) \leq E_{OL}(D)$, where:

$$
E_{OL}(D) = \begin{cases} 
\frac{2\sigma^2}{1-\rho^2} \log \left( \frac{\sigma_1^2(1+|\rho_s|)}{D(1-2\rho_z)+\sigma_1^2|\rho_s|} \right), & D \geq D_{th}, \\
\frac{2\sigma^2}{1-\rho^2} \log \left( \frac{(2-\rho_z)(1+|\rho_s|)}{D(2-\rho_z)} \right), & D < D_{th}.
\end{cases}
$$

**Proof Outline:** In [13, Sec. VB] we derive an upper bound on $K_{OL}(P, D)$, denoted by $K_{OL}^{up}(P, D)$. We further show that $K_{OL}^{up}(P, D) \to 1$ and that $K_{OL}(P, D) \to \infty$ as $P \to 0$. As both sources generate their realizations at a fixed rate, the above limit ratio implies that the bandwidth used by the OL scheme increases to infinity as $P \to 0$. Next, recalling that $E_{OL}(D) = P \cdot K_{OL}(P, D)$, we evaluate $P \cdot K_{OL}^{up}(P, D)$ as $P \to 0$, and obtain an upper bound on $E_{OL-min}(D)$. The detailed proof is provided in [13, Sec. C].

**Remark 3.** It can be observed that when the sources are independent, i.e., $\rho_s = 0$, then $E_{OL}(D) = E_{sep}^{(\rho_z)}(D) = E_{sep}^{(\rho_z)}(D)$, for all $0 \leq D \leq \sigma_1^2$. When $|\rho_s| \to 1$ and $\rho_z \to 1$ then $E_{OL}(D) \to E_{th}(D) \approx \sigma_1^2 \log \left( \frac{\sigma_1^2}{\rho_z} \right)$, in this case we also have $E_{sep}^{(\rho_z)}(D) \to E_{th}(D)$ and $E_{sep}^{(\rho_z)}(D) \approx 2E_{OL}(D)$.

**Remark 4.** In this work we did not analyze the EDT of JSCC using the LQG scheme, $E_{LQG}(D)$. The reason is two-fold: analytic tractability and practical relevance. We note that in [12, Sec. 4] we adapted the LQG scheme for [11] to the transmission of correlated Gaussian sources over GBCFs. We have observed in [11] that obtaining a closed-form expression for $E_{LQG}(D)$ seems intractable. Yet, using the results and analysis of [12] one can find good approximations for $E_{LQG}(D)$. We also showed in [12] that, in the context of JSCC, and in contrast to the results of [12] for the channel coding problem, when the duration of transmission is finite and the transmission power is very low, the OL scheme outperforms the LQG scheme. This conclusion is expected to hold for the EDT as well. Indeed, numerical simulations indicate that the LQG scheme of [12, Sec. 4] achieves roughly the same minimum energy as the SSCC-$\rho_z$ scheme, while in Section IV we show that the OL scheme outperforms the SSCC-$\rho_z$ scheme.

**IV. Numerical Results**

Next, we numerically compare $E_{th}(D)$, $E_{sep}^{(\rho_z)}(D)$, $E_{sep}^{(\rho_z)}(D)$ and $E_{OL}(D)$. We set $\sigma_1^2 = \sigma_2^2 = 1$ and consider several values of $\rho_z$ and $\rho_s$. Fig. 2 depicts $E_{th}(D)$, $E_{sep}^{(\rho_z)}(D)$, $E_{sep}^{(\rho_z)}(D)$ and $E_{OL}(D)$ for $\rho_z = 0.5$, and for two values of $\rho_s$: $\rho_s = 0.2$ and $\rho_s = 0.9$. As $E_{sep}^{(\rho_z)}(D)$ is not a function of $\rho_s$, it is plotted only once. It can be observed that when $\rho_s = 0.2$, $E_{sep}^{(\rho_z)}(D)$ and $E_{OL}(D)$ are almost the same. This follows because when the correlation between the sources is low, the gains from accounting for this correlation are also low. Furthermore, when $\rho_s = 0.2$, the gap between the lower bound and the upper bounds is evident. On the other hand, when $\rho_s = 0.9$, both SSCC-$\rho_s$ and OL significantly improve upon SSCC-$\rho_z$. This follows as SSCC-$\rho_z$ does not take advantage of the correlation among the sources. It can further be observed that when the distortion is low, there is a small gap between OL and SSCC-$\rho_s$, while when the distortion is high, OL and SSCC-$\rho_s$ require roughly the same amount of energy. This is also supported by Fig 4. We conclude that as the SSCC-$\rho_s$ scheme encodes over long sequences of source samples, it better exploits the correlation among the sources compared to the OL scheme.

Fig. 3 depicts $E_{th}(D)$, $E_{sep}^{(\rho_z)}(D)$, $E_{sep}^{(\rho_z)}(D)$ and $E_{OL}(D)$ vs. $D$, for $\rho_s = 0.8$, and for $\rho_z \in \{-0.9, 0.9\}$. As $E_{sep}^{(\rho_z)}(D)$ and
other hand, the gap between the energy requirements of the SSCC-$\rho_s$ scheme and the uncoded JSCC OL scheme. We concluded that while the OL scheme provides an attractive alternative for energy efficient transmission over GBCFs.

Therefore, the OL scheme outperforms SSCC-$\rho_s$ for low $D_s$, or for high $D$, $E_{\text{sep}}(D) \approx E_{\text{OL}}(D)$. On the other hand, when $|\rho_s|$ is large and $D$ is low, the SSCC-$\rho_s$ scheme improves upon the OL scheme. Fig. 5 depicts the difference $E_{\text{sep}}(D) - E_{\text{OL}}(D)$ for $\rho_z = 0.5$. It can be observed that larger $|\rho_s|$ results in a larger gap.

V. CONCLUSIONS

This work is a first step towards characterizing the optimal EDT for sending correlated Gaussian sources over GBCFs, where no restriction is placed on the signaling scheme or the source-channel bandwidth ratio. In particular, we first lower bounded the minimum required energy per source-pair sample using cut-set arguments, and then upper bounded it by analyzing three transmission schemes: Two different SSCC schemes, and the uncoded JSCC OL scheme. We concluded that while SSCC-$\rho_s$ successfully exploits the correlation between the sources by jointly encoding the source sequences into a single bit stream, SSCC-$\rho_z$ does not exploit the correlation between the noise components since the LQG channel coding scheme of [11] achieves the same minimum energy per pair of bits as orthogonal transmission. This leads to the conclusion that SSCC-$\rho_s$ outperforms SSCC-$\rho_z$. Numerical results indicate that SSCC-$\rho_s$ outperforms the OL scheme as well. On the other hand, the gap between the energy requirements of the two schemes is rather small. We note that, in the SSCC-$\rho_z$ scheme coding takes place over multiple samples of source pairs which introduces high computational complexity, large delays, and requires large amount of storage. On the other hand, the OL scheme applies linear and uncoded transmission to each source sample pair separately, which requires low computational complexity, short delays, and limited storage.

References

[1] A. Jain, D. Gündüz, S. R. Kulkarni, H. V. Poor, and S. Verdú, “Energy-distortion tradeoffs in Gaussian joint source-channel coding problems,” IEEE Trans. Inf. Theory, vol. 58, no. 5, pp. 3153–3168, May 2012.
[2] F. Alagöz, and G. Gür, “Energy efficiency and satellite networking: A holistic overview,” Proc. of IEEE, vol. 99, no. 11, pp. 1954–1979, Nov. 2011.
[3] T. Rault, A. Bouabdallah, and Y. Challal, “Energy efficiency in wireless sensor networks: A top-down survey,” Computer Networks, vol. 67, pp. 104–122, 2014.
[4] G. D. Nion, A. S. Lioumpas, and K. S. Nikita, “Reliable and energy-efficient communications for wireless biomedical implant systems,” IEEE Jour. Med. Health Inform., vol. 18, no. 6, pp. 1848–1856, Nov. 2014.
[5] C. E. Shannon, “Coding theorems for a discrete source with a fidelity criterion,” IRE Int. Conv. Rec., vol. 7, part 4, pp. 142–163, 1959.
[6] T. M. Cover, A. El. Gamal, and M. Salehi, “Multiple access channels with arbitrarily correlated sources,” IEEE Trans. Inf. Theory, vol. 26, no. 6, pp. 648–657, Nov. 1980.
[7] L. Ong and M. Motani, “Coding strategies for multiple-access channels with feedback and correlated sources,” IEEE Trans. Inf. Theory, vol. 53, no. 10, pp. 3476–3497, Oct. 2007.
[8] A. Lapidoth and S. Tinguely, “Sending a bivariate Gaussian source over a Gaussian MAC with feedback,” IEEE Trans. Inf. Theory, vol. 56, no. 4, pp. 1852–1864, Apr. 2010.
[9] L. H. Ozarow and S. K. Leung-Yan-Cheong, “An achievable region and outer bound for the Gaussian broadcast channel with feedback,” IEEE Trans. Inf. Theory, vol. 30, no. 4, pp. 667–671, Jul. 1984.
[10] N. Elia, “When Bode meets Shannon: Control oriented feedback communication schemes,” IEEE Trans. Automat. Control, vol. 49, no. 9, pp. 1477–1488, Sep. 2004.
[11] E. Ardestanizadeh, P. Minero and M. Franceschetti, “LQG control approach to Gaussian broadcast channels with feedback,” IEEE Trans. Inf. Theory, vol. 58, no. 8, pp. 5267–5278, Aug. 2012.
[12] Y. Murin, Y. Kaspi, R. Dabora, and D. Gündüz, “Finite-length linear schemes for joint source-channel coding over Gaussian broadcast channels with feedback,” submitted to IEEE Inf. Theory, under revision. Available at http://web.stanford.edu/~moriny.
[13] Y. Murin, Y. Kaspi, R. Dabora, and D. Gündüz, “On the energy-distortion tradeoff of Gaussian broadcast channels with feedback,” submitted to IEEE Trans. Commun.. Available at http://web.stanford.edu/~moriny.
[14] A. Lapidoth and S. Tinguely, “Sending a bivariate Gaussian source over a Gaussian MAC,” IEEE Trans. Inf. Theory, vol. 56, no. 6, pp. 2714–2752, Jun. 2010.
[15] T. M. Cover and J. A. Thomas, Elements of Information Theory. John Wiley and Sons Inc., 1991.
[16] S. Verdú, “On channel capacity per unit cost,” IEEE Trans. Inf. Theory, vol. 36, no. 5, pp. 1091–1030. Sep. 1990.
[17] S. B. Amor, Y. Steinberg and M. Wigger, “MIMO MAC-BC duality with linear-feedback coding schemes,” IEEE Trans. Inf. Theory, vol. 61, no. 11, pp. 5976–5998, Nov. 2015.