Is Analog Network Coding More Energy Efficient than TDMA?

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***Abstract*—In this paper, we investigate the possibility, from an energy efficiency point of view, of employing Analog Network Coding in the Multiple Access Relay Channel (MARC) instead of the conventional Time-Division Multiple Access (TDMA) protocol when time and not bandwidth is the available resource in the network. Towards this end, we derive a closed-form upper bound of the Bit Error Rate (BER) per source of Analog Network Coding when the optimal maximum-likelihood (ML) detector is employed. Based on this framework, we mathematically prove that as either the number of sources or the number of relays or the modulation order increases, the possibility of Analog Network Coding being more energy efficient than TDMA increases as well. These findings are substantiated by means of Monte Carlo simulations.**

I. Introduction

Network Coding achieves the maximum information flow in a network with multiple nodes by enabling the intermediate nodes to perform coding operations at the incoming packets [1]. Although initially aimed for wired networks, Network Coding can be readily extended to wireless networks that consist of intermediate nodes between the sources and the destination, such as relays [2].

There are several Network Coding techniques proposed, among which the amplify-and-forward approach, which is termed as Analog Network Coding [3], has the lowest complexity since the only operations that the relays perform at the incoming signals is amplification and forwarding to the destination. Hence, it is considered as an attractive option for future relay-based systems that employ Network Coding, especially when the relays are battery-powered terminals in which the relaying operations should be kept as simple as possible. In addition, the exploitation of relays for the end-to-end communication of mobile terminals with the Base Station is included in current wireless standards, such as WiMAX and LTE-Advanced [4]. Hence, the resulting Multiple Access Relay Channel (MARC) is a typical uplink scenario of future wireless networks where Analog Network Coding can find implementation.

Since its introduction, there have been several works in the literature exploiting Analog Network Coding in the MARC from an information-theoretic point of view [5]-[8] (and references therein). Although these works are important in the sense that they examine the information-theoretic capabilities of Analog Network Coding, designers of practical systems are also interested in the expected system diversity and error probabilities when employing a particular modulation scheme. Towards this end, in [9] the authors present a diversity analysis of Analog Network Coding schemes that employ relay selection and distributed space-time coding [10] when the optimal ML detector is applied. However, the time-orthogonal transmission protocol from the relays can be a better alternative when a feedback channel is not feasible (relay selection) and when relay synchronization poses significant practical challenges (distributed space-time coding).

Contribution: In this work, we provide an energy efficiency comparison of Analog Network Coding with the TDMA protocol in the MARC with time-orthogonal transmission from the relays. This evaluation, which to the best of our knowledge has not been reported in the literature, is important since it gives an answer to whether Analog Network Coding or TDMA is to be preferred, energy-wise, when time and not bandwidth is the only available resource in the network. In addition, we mathematically prove that as either the number of sources or the number of relays or the modulation order increases, the possibility of Analog Network Coding being more energy efficient than TDMA increases as well.

Organization: The rest of the paper is organized as follows: Section II presents the system model under consideration. In Section III, a high-SNR closed-form formula of the BER per source of Analog Network coding with ML detection is presented, which is based on previous reported results. Moreover, based on this formula, the energy efficiency comparison of Analog Network Coding with TDMA is investigated. In Section IV, numerical results are provided, which substantiate the analytical derivations, and, finally, Section V concludes this work.

Notation: The following notation is used throughout this paper: i) $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty \exp(-u^2/2)du$ denotes the Q-function; ii) $E\{x\}$ denotes the mean value of the stochastic process x; iii) $|\cdot|$ and $\|\cdot\|_F^2$ are the absolute value and Frobenious norm, respectively, iv) $\log(\cdot)$ is the natural logarithm,

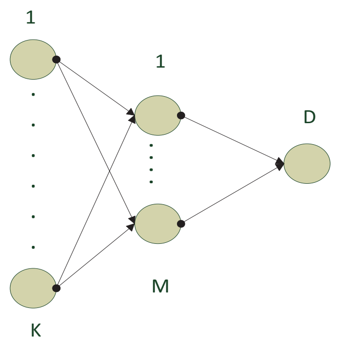

Fig. 1: The Multiple Access Relay Channel.

v) $diag[\cdot]$ takes as argument a vector and denotes a diagonal matrix with the elements of the vector as the elements of the main diagonal, and vi) matrices and vectors are denoted in boldface.

II. System Model

We consider the MARC depicted in Fig. 1, which is a typical uplink scenario for next generation cellular networks. K sources want to communicate with a common destination through the use of M fixed-gain and half-duplex relays. We assume that all the nodes are equipped with a single antenna and that no direct link exists between the sources and the destination, which can be attributed to a heavy-shadowing environment, for instance. Let $h_{km} \sim \sigma_{km}^2 CN(0,1)$ be the channel coefficient from the k_{th} source to the m_{th} relay and $f_m \sim \sigma_{m_D}^2 CN(0,1)$ the channel coefficient from the m_{th} relay to the destination, $k = 1, 2, ..., K$, $m = 1, 2, ..., M$, where σ_{km}^2 and $\sigma_{m_D}^2$ are the path-loss coefficients (including shadowing effects) of the source-relay and relay-destination links, respectively. To simplify the notations and for analytical tractability of the derivations in the following sections, we assume that $\sigma_{km}^2 = \sigma_{SR}^2$ and $\sigma_{m_D}^2 = \sigma_{RD}^2$. Physically, this means that the sources and the relays are clustered and, hence, the path-loss coefficients of the source-relay and relay-destination links can be considered equal, respectively. Moreover, each source has the packet s_k to be dispatched to the destination, which perfectly knows the instantaneous values of h_{km} and f_m. In addition, the relays have statistical knowledge of the source-relay links, which means that they are aware of σ_{SR}^2. Finally, without loss of generality, we consider that the sources and the relays have equal transmission powers, which are denoted as P_S and P_R, respectively.

Two transmission phases in the system are distinguished:

1st Phase-Transmission from the sources to the relays: During the first phase, which has a duration of 1 time slot, the K sources simultaneously transmit their modulated packets s_k to the relays. Hence, the received signal y_m at the m_{th} relay is given by

$$y_m = \sum_{k=1}^{K} \sqrt{P_S \sigma_{SR}^2} h_{km} s_k + n_m, \tag{1}$$

where $n_m \sim CN(0,1)$ is the Additive White Gaussian Noise realization at m_{th} relay. In addition, we ideally assume that the incoming signals form the sources arrive at the relays at the same time and, hence, there is perfect synchronization at the relays.

2nd Phase-Transmission from the relays to the destination: During the second phase, the fixed-gain relays amplify their received signal and forward it to the destination. As a case-study, we consider the time-orthogonal transmission protocol from the relays, which means that they forward their signal to the destination one after the other in non-overlapping time slots. Based on this protocol, $M+1$ time slots are required for the end-to-end communication between the sources and the destination.

The gain r_m of the relays, which normalizes their average transmission power with respect to the average received power of the sources, is given by [12]

$$r_m = \sqrt{\frac{1}{KP_S\sigma_{SR}^2 + 1}}. \tag{2}$$

Consequently, the received signal at the destination from each of the relays is

$$\begin{aligned} y_{D_m} &= \sqrt{P_R \sigma_{RD}^2} r_m y_m f_m + n_D \\ &= \sqrt{\frac{P_S\sigma_{SR}^2 P_R \sigma_{RD}^2}{KP_S\sigma_{SR}^2 + 1}} f_m \sum_{k=1}^{K} h_{km} s_k + \tilde{n}_{Dm}, \end{aligned} \tag{3}$$

where $n_D \sim CN(0,1)$ and $\tilde{n}_{Dm} \sim CN\left(0, \frac{P_R\sigma_{RD}^2}{KP_S\sigma_{SR}^2+1}|f_m|^2 + 1\right)$. In matrix form, (3) can be written as

$$\mathbf{y} = \sqrt{\frac{P_S\sigma_{SR}^2 P_R\sigma_{RD}^2}{KP_S\sigma_{SR}^2 + 1}} \mathbf{FHs} + \tilde{\mathbf{n}}_D, \tag{4}$$

where $\mathbf{F} = diag\left[\begin{pmatrix} f_1 & \cdots & f_M \end{pmatrix}\right]$, $\mathbf{s} = \begin{pmatrix} s_1 & \cdots & s_K \end{pmatrix}^T$, $\tilde{\mathbf{n}}_D = \begin{pmatrix} \tilde{n}_{D_1} & \cdots & \tilde{n}_{D_M} \end{pmatrix}^T$, and $\mathbf{H} \in \mathbb{C}^{M \times K}$ with h_{km} as entries.

It is clear from (4) that the MARC with Analog Network Coding is equivalent to a spatial multiplexing Multiple-Input-Multiple-Output (MIMO) system [13] with channel matrix $\mathbf{FH}$.

III. BER per Source of Analog Network Coding and Energy Efficiency Comparison with TDMA

In this section, we first derive a closed-form formula of the BER per source of Analog Network Coding and, subsequently, we perform its energy efficiency comparison with TDMA, based on the derived expression.

A. BER per Source

By having the channel coefficients that correspond to the source-relay and relay-destination links, the destination can employ the optimal maximum-likelihood detection and jointly obtain the transmitted symbols from the sources as

$$\mathbf{s}_{det} = \arg\min_{\hat{s}_k} \sum_{m=1}^{M} \frac{\left| y_{D_m} - \sqrt{\frac{P_S \sigma_{SR}^2 P_R \sigma_{RD}^2}{K P_S \sigma_{SR}^2 + 1}} f_m \sum_{k=1}^{K} h_{km} \hat{s}_k \right|^2}{\frac{P_R \sigma_{RD}^2}{K P_S \sigma_{SR}^2 + 1} |f_m|^2 + 1}, \tag{5}$$

where $\mathbf{s}_{det} = \begin{pmatrix} s_{1_{det}} & \cdots & s_{K_{det}} \end{pmatrix}^T$ is the detected symbol vector.

Based on (5), we aim to derive an analytical closed-form framework for the Union Bound of the BER per source. Considering that the MARC with Analog Network Coding and sequential time-orthogonal transmission from the relays is equivalent to a spatial multiplexing MIMO system, as we showed in Section II, then, based on [13], with $\{s_q\}$ we denote the set of all possible Q symbols transmitted from a particular source, which we assume to be equally probable. Furthermore, with $\{\mathbf{s}\}$ we denote the set of the Q^K symbol vectors to be transmitted form the K sources, with $\{\mathbf{s}_i\}$ we define a subset of $\{\mathbf{s}\}$ in which the symbol vectors have s_q transmitted from the k_{th} source, so in total there are Q^{K-1} such vectors, and, finally, with $\{\mathbf{s}_j\}$ we denote the set of the $Q^K - Q^{K-1}$ symbol vectors in which the symbol transmitted from the k_{th} source is different than s_q. Assuming that all the sources employ the same modulation order Q, the union bound of the Symbol Error Rate per source for ML detection, which we denote as SER_{ML}, is given by

$$SER_{ML} \leqslant Q^{-K} \sum_{q=1}^{Q} \sum_{i=1}^{Q^{K-1}} \sum_{j=1}^{Q^K - Q^{K-1}} PEP_{s_q,ij}, \tag{6}$$

where $PEP_{s_q,ij}$ denotes the pairwise error probability (PEP) of detecting the symbol vector $\mathbf{s}_j$ when the vector $\mathbf{s}_i$ is transmitted. By considering (5), $PEP_{s_q,ij}$ is given by

$$PEP_{s_q,ij} = E\left\{ Q\left(\sqrt{V(h,f)} \right) \right\}, \tag{7}$$

where $V(h,f) = \sum_{m=1}^{M} \frac{1}{2} \frac{P_S \sigma_{SR}^2 P_R \sigma_{RD}^2 |\mathbf{h}_m \boldsymbol{\Delta}\mathbf{s}_{i,j}|^2 |f_m|^2}{P_R \sigma_{RD}^2 |f_m|^2 + K P_S \sigma_{SR}^2 + 1}$, $\mathbf{h}_m = \begin{pmatrix} h_{1m} & h_{2m} \cdots h_{Km} \end{pmatrix}$ and $\boldsymbol{\Delta}\mathbf{s}_{i,j} = \mathbf{s}_i - \mathbf{s}_j$. By considering the exponential approximation of the Q-function [14, (31)]:

$$Q(x) \approx \frac{1}{12} e^{-\frac{x^2}{2}} + \frac{1}{6} e^{-\frac{2x^2}{3}}, \tag{8}$$

in [15] we prove that

$$PEP_{s_q,ij} \approx \frac{1}{12} \left[\frac{1}{b+1} + \frac{bc}{a(b+1)^2} Z\left(\frac{c}{a(b+1)} \right) \right]^M + \frac{1}{6} \left[\frac{3}{4b+3} + \frac{12bc}{a(4b+3)^2} Z\left(\frac{3c}{a(4b+3)} \right) \right]^M, \tag{9}$$

where $Z(x) = e^x E_1(x)$, $a = P_R \sigma_{RD}^2$, $b = \frac{1}{4} P_S \sigma_{SR}^2 \|\boldsymbol{\Delta}\mathbf{s}_{i,j}\|_F^2$, and $c = K P_S \sigma_{SR}^2 + 1$. Consequently, by plugging (9) into (6) we obtain the Union Bound of the SER per source.

Regarding the BER, an approximate upper bound can be obtained by dividing (6) with the transmitted number of bits per source [13]. Hence,

$$BER \leqslant \frac{Q^{-K} \sum_{q=1}^{Q} \sum_{i=1}^{Q^{K-1}} \sum_{j=1}^{Q^K - Q^{K-1}} PEP_{s_q,ij}}{\log_2(Q)}. \tag{10}$$

B. Energy Efficiency Comparison of Analog Network Coding with the TDMA Protocol

Without performing network coding operations at the relays and by considering that only time is available as a resource and not bandwidth, which is a plausible scenario when there are many sources (users) inside a cell, then the only way to serve all the sources is by the TDMA approach. In this case, the sources are served sequentially and at any given time the bandwidth resources are used only by one source. Since in TDMA $M+1$ time slots are required for the end-to-end transmission of one source, in total $K(M+1)$ time slots are required for the end-to-end transmission of the K sources. Assuming that the sources and relays use the same power level, denoted as P_{TDMA},the total power used in the network in these $K(M+1)$ time slots, which we denote as P_{total}^{TDMA}, is given by

$$P_{total}^{TDMA} = K(M+1) P_{TDMA}. \tag{11}$$

On the other hand, since in Analog Network Coding there is simultaneous transmission from the sources to the relays, only $M+1$ time slots are required for the end-to-end transmission of the K sources. Hence, in $K(M+1)$ time slots that are required for the end-to-end transmission of the K sources in TDMA, K rounds of end-to-end transmission occur in the Analog Network Coding case. Consequently, by assuming the same power level of the sources and the relays, which we denote as P_{ANC}, the total power used in the network in these $K(M+1)$ time slots, which we denote as P_{total}^{ANC}, is given by

$$P_{total}^{ANC} = K^2 P_{ANC} + K M P_{ANC} = K(K+M) P_{ANC}. \tag{12}$$

In addition, if Q_{ANC} is the modulation order of the sources used in the Analog Network Coding case, then in the TDMA protocol the sources need to employ a modulation order Q_{TDMA} that is given by

$$Q_{TDMA} = Q_{ANC}^K \tag{13}$$

to match the same number of bits per source transmitted with the one of the Analog Network Coding case.

Now, to make a fair energy requirement comparison of Analog Network Coding with TDMA we assume that the total available power in both cases is the same, which means that

$$P_{total}^{ANC} = P_{total}^{TDMA} \overset{(11),(12)}{\Rightarrow} (K+M) P_{ANC} = (M+1) P_{TDMA}. \tag{14}$$

Considering (14), if Analog Network Coding achieves a smaller BER per source than TDMA, then it better energy efficiency or the other way round if the opposite happens. Consequently, to examine the energy saving prospects of Analog Network Coding with respect to the TDMA protocol, we formulate the ratio

$$r_{TDMA/ANC} = \frac{BER_{TDMA}}{BER_{ANC}}. \quad (15)$$

If $r_{TDMA/ANC} > 1$, Analog Network Coding is the preferred choice, energy-wise, otherwise TDMA is the preferred solution. BER_{TDMA} is obtained from (10) by setting $K = 1$ at the enumerator and $Q_{TDMA} = Q_{ANC}^{K}$ at the denominator, since the transmission takes place sequentially among the sources.

Theorem 1: $r_{TDMA/ANC}$ is a monotonically increasing function of i) K, ii) M, and ii) Q_{ANC}. This means that the possibility of using Analog Network Coding instead of TDMA increases for increasing K, M, and Q_{ANC}.

Proof: See APPENDIX.

IV. Numerical Results

In this section, our aim is to substantiate the proven monotonic trends in Section III regarding the energy gain of Analog Network Coding over TDMA with respect to the number of sources, the number of relays, and the modulation order.

Assuming that P_{total}^{TDMA} and P_{total}^{ANC} are the total powers of the sources and relays required to achieve a target BER in the TDMA and Analog Network Coding case, respectively, based on Section III-B, the relative energy gain that is achieved by the use of Analog Network Coding instead of TDMA for the particular target BER is defined as

$$relative\ energy\ gain = \frac{P_{total}^{TDMA} - P_{total}^{ANC}}{P_{total}^{TDMA}}\ [\%]\,. \quad (16)$$

In Table I and Table II, we illustrate this gain for a target BER of 10^{-4}, $\sigma_{SR}^2 = \sigma_{RD}^2 = 1$, different number of sources, relays, and two values for the modulation order. To obtain the P_{total}^{TDMA} and P_{total}^{ANC} values to achieve this target BER, we used the analytical framework for the BER of (10).

TABLE I: Relative Energy Gain (%) of Analog Network Coding over TDMA for $Q_{ANC} = 2$ (BPSK).

$K=2$	$K=3$	$K=4$	$K=5$	$K=6$
$M=1$				
-100	-100	-100	-58	-20
$M=2$				
-32	-5	37	65	84
$M=3$				
-15	26	63	83	93
$M=4$				
-5	37	72	89	96

The values of Table I and Table II corroborate the proven monotonic trends of $r_{TDMA/ANC}$ of (15) with respect to the number of sources, the number of relays, and the modulation order. In particular, we see that the higher the number of sources or the number of relays or the modulation order of the sources is, the better it is for Analog Network Coding, energy-wise, as expected. From these Tables we also observe that Analog Network Coding is less energy efficient than TDMA only for few cases, in particular when the value Q_{ANC} is small and when the value of either K or M or both is small as well.

TABLE II: Relative Energy Gain (%) of Analog Network Coding over TDMA for $Q_{ANC} = 4$ (QPSK).

$K=2$	$K=3$
$M=1$	
9	48
$M=2$	
58	91
$M=3$	
72	95
$M=4$	
77	97

Finally, we should also note that in Table I and Table II we presented results for number of sources up to 6 and 3, respectively, since this means that the employed maximum modulation order for TDMA to keep the same rate per source for these number of sources is 64 QAM, based on (13), which is the highest modulation order allowed according to the current wireless standards, such as LTE.

V. Conclusions

In this paper, we investigated the possibility, from an energy efficiency point of view, of employing Analog Network Coding in the MARC instead of TDMA and we mathematically proved that as the number of sources or relays or the modulation order increases, the possibility of Analog Network Coding being more energy efficient than TDMA increases as well, when the optimal ML detector is employed. To the best of our knowledge, such a comparison has not been conducted in the literature before and these findings can be used to choose whether to employ Analog Network Coding or TDMA, based on the scenario. In particular, the numerical results showed that Analog Network Coding becomes significantly more energy efficient than TDMA for increasing number of sources or relays or modulation order.

Acknowledgment

This work has received funding from the the GREENET (264759) research project and has been supported by the Generalitat de Catalunya under grant 2014-SGR-1551.

Appendix

A. *Proof of Theorem 1*:

Preliminaries: Considering the high-SNR region, then

$$r_{TDMA/ANC} \overset{P_{ANC}\to\infty,\,(11),\,(12),\,(14)}{\approx} \frac{1}{K}\left[\frac{2(M+1)}{(K+1)(K+M)}\right]^{M} \times \frac{\sum\limits_{\mathbf{\Delta s}} \frac{1}{\left(|\mathbf{\Delta s}_{i,j}|_F^2\right)_{TDMA}^M}}{\sum\limits_{\mathbf{\Delta s}} \frac{1}{\left(|\mathbf{\Delta s}_{i,j}|_F^2\right)_{ANC}^M}}. \quad (17)$$

To simplify things, we consider only the the closest neighbors in the error vectors $\mathbf{\Delta s}_{i,j}$ of (17). Hence, due to the geometry of a square QAM constellation it holds that:

$$\sum_{\mathbf{\Delta s}} \frac{1}{\left(|\mathbf{\Delta s}_{i,j}|_F^2\right)_{ANC}^M} \approx 4\left(Q_{ANC} - \sqrt{Q_{ANC}}\right) \times \left[\frac{(Q_{ANC}-1)}{6}\right]^M Q_{ANC}^{K-1} \quad (18a)$$

$$\sum_{\mathbf{\Delta s}} \frac{1}{\left(|\mathbf{\Delta s}_{i,j}|_F^2\right)_{TDMA}^M} \approx 4\left(Q_{TDMA} - \sqrt{Q_{TDMA}}\right) \times \left[\frac{(Q_{TDMA}-1)}{6}\right]^M = 4\left(Q_{ANC}^K - \sqrt{Q_{ANC}^K}\right) \times \left[\frac{(Q_{ANC}^K-1)}{6}\right]^M. \quad (18b)$$

(18a) and (18b) hold because $\frac{6}{Q-1}$ is the minimum squared Euclidean Distance of a square QAM constelation of order Q and $4\left(Q-\sqrt{Q}\right)$ is the total number of minimum squared Euclidean distances of the same constellation. Hence, by plugging (18a) and (18b) into (17), we get

$$r_{TDMA/ANC} \approx \frac{1}{K}\left[\frac{2(M+1)\left(Q_{ANC}^K-1\right)}{(K+1)(K+M)(Q_{ANC}-1)}\right]^M \times \frac{\left(Q_{ANC}^K - \sqrt{Q_{ANC}^K}\right)\left(Q_{ANC}^K-1\right)}{\left(Q_{ANC}-\sqrt{Q_{ANC}}\right)Q_{ANC}^{K-1}}. \quad (19)$$

i) *Proving that $r_{TDMA/ANC}$ is a monotonically increasing function of K*:

$$\frac{d\left(r_{TDMA/ANC}\right)}{dK} > 0 \Rightarrow (K+M) \times \log\left(Q_{ANC}\right)(M+1) > (2M+1) + KM^2 + M \quad true. \quad (20)$$

ii) *Proving that $r_{TDMA/ANC}$ is a monotonically increasing function of M*:

$$\frac{d\left(r_{TDMA/ANC}\right)}{dM} > 0 \Rightarrow (K+1)(K+M) \times \log\left[\frac{2(M+1)\left(Q_{ANC}^K-1\right)}{(K+1)(K+M)(Q_{ANC}-1)}\right] + (K-1)M > 0 \quad true, \quad (21)$$

since

$$\log\left[\frac{2(M+1)\left(Q_{ANC}^K-1\right)}{(K+1)(K+M)(Q_{ANC}-1)}\right] \geqslant 0 \Rightarrow \frac{Q_{ANC}^K-1}{Q_{ANC}-1} \geqslant \frac{(K+1)(K+M)}{2(M+1)} \quad true. \quad (22)$$

iii) *Proving that $r_{TDMA/ANC}$ is a monotonically increasing function of Q_{ANC}*:

$$\frac{d\left(r_{TDMA/ANC}\right)}{dQ_{ANC}} > 0 \overset{Q_{ANC}\gg 1}{\Rightarrow} M(K-1)+K > \frac{1}{2\sqrt{Q}_{ANC}} \quad true. \quad (23)$$

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