Multicast MIMO Enhancement for V2X over LTE

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***Abstract*—Motivated by recent interest in vehicle-to-vehicle/ infrastructure/pedestrian (V2X) communication over the fourth generation of the Long-Term Evolution (LTE) cellular standard, we study the efficiency of the Multimedia Broadcast Multicast Services (MBMS), a key enabler for V2X communication, which currently employs only single antenna transmission. We show that by utilizing more transmit antennas at the base station — which are already used for point-to-point communications — and simple space–time coding (STC) techniques, a significant boost in performance can be achieved. To this end, we evaluate the performance of different transmission strategies along with the information theoretic optimal performance. For a fast Rayleigh fading channel, we show that a gain of 1 bit/sec/Hz is achieved for a signal-to-noise ratio of 10dB, and higher gains for higher signal-to-noise-ratios for for an outage probability of 0.01. Moreover, we demonstrate that Alamouti STC is near optimum for typical signal-to-noise ratios. However, for more antennas, due to the inherent loss of multiplexing of orthogonal STC schemes, non-orthogonal STC schemes with higher multiplexing need to be considered.**

***Index Terms*—Physical-layer multicast, common-message broadcast, space–time coding, MBMS, MIMO, V2X, V2V.**

I. Introduction

The concept of the *connected vehicle* is perceived as the next game-changer in the automotive industry and ecosystem [1], aiming to revolutionize all automotive aspects: from the way we use our vehicles (social commuting, traffic/parking management), through the way we own our vehicles (car sharing), and to the way we drive our vehicles (autonomous driving). Generally, the connected vehicle concept requires ubiquitous V2X (V2V — vehicle-to-vehicle, V2I — vehicle-to-infrastructure, V2P — vehicle-to-pedestrian) connectivity, which translates into high throughput, low latency and highly reliable wireless communication links over fast fading wireless channels (due to the high mobility of vehicles). The exact requirements are derived from the application, with safety related applications, e.g., (semi) autonomous driving, being the most stringent ones.

Recently, the fourth generation of the Long Term Evaluation (LTE) cellular standard was suggested for the purposes of V2X connectivity [2], and a new 3rd generation partnership project (3GPP) standardization study group, that focuses on LTE-based V2X communications [3], was established. Indeed, LTE is an attractive technology that offers three related major services: (i) unicast, (ii) device-to-device communication, (iii) multicast, i.e., Multimedia Broadcast Multicast Services (MBMS) [4]. MBMS is a key enabler for safety related applications, due to their broadcast nature[1], and the clear understanding that if V2X over LTE is to become a reality, it has to be efficient in a way that will not disrupt other operator's services.

Motivated by these trends, the focus of this study is on improving the MBMS spectral efficiency for V2X over LTE applications. Generally, MBMS is resource efficient, since it transforms multiple unicast transmissions into a single multicast. MBMS defines a region, that may include several base stations that cooperate and multicast the same signal at the same time and at the same band for all users in this region. This technique mitigates the interferences that traditionally limited the unicast transmission, improving the received signal-to-interference-and-noise ratio (SINR). Furthermore, it potentially makes SINR more uniform across the entire MBMS region except for its edges; the larger the MBMS region is, the smaller the effect of it edges (relative to the entire MBMS region's area). Nowadays, both the base stations and the vehicles/user equipments (UEs) are equipped with at least two antennas. Nevertheless, MBMS is standardized to multicast data over a single transmit antenna, and it doesn't take advantage of the potential multiple-input multiple-output (MIMO) capability. In this study, we propose and analyze the use of multiple-stream schemes as well as diversity oriented schemes, i.e., orthogonal block space–time coding (OSTBC) schemes, such as the Alamouti OSTBC scheme [5], to improve the MBMS spectral efficiency by leveraging the multiple antennas both at the base stations and at the UEs. We focus on a single base station transmitting to multiple UEs, where extending it to multiple base stations that multicast identical transmission simultaneously is trivial. We shall limit our discussion only to open loop schemes, i.e., where no channel state information (CSI) is available at the base stations.

II. Channel Model and Communications Setting

We consider a 2×2 flat Rayleigh fading channel model:

$$\begin{bmatrix} y_1[i] \\ y_2[i] \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1[i] \\ x_2[i] \end{bmatrix} + \begin{bmatrix} z_1[i] \\ z_2[i] \end{bmatrix},$$

or equivalently

$$\boldsymbol{y}[i] = \mathbf{H}\boldsymbol{x}[i] + \boldsymbol{z}[i], \tag{1}$$

where $i = 1, \ldots, N$ is the time index, $\boldsymbol{y} = \begin{bmatrix} y_1[i] & y_2[i] \end{bmatrix}^T$ is the channel output vector, $\mathbf{H} = [h_{mn}]$ is the channel matrix with i.i.d. circularly-symmetric Gaussian entries of power ρ which remains constant throughout the transmission block, $\boldsymbol{x} = \begin{bmatrix} x_1[i] & x_2[i] \end{bmatrix}^T$ is the channel input vector subject to

[1] Most safety related applications require a short message broadcast to all vehicles in close vicinity in events like emergency stop, loss of control, etc.

an average individual (per-element) power constraint 1,[2] and $\boldsymbol{z} = \begin{bmatrix} z_1[i] & z_2[i] \end{bmatrix}^T$ is an i.i.d. Gaussian circularly-symmetric noise vector with zero mean and identity covariance matrix.

We assume an *open-loop* scenario, meaning that the channel matrix $\mathbf{H}$ is known to the receiver but not to the transmitter. This is a standard model that represents a (down)link between a single base station and a single UE equipped with two antennas each.

We extend it to the multicast scenario by considering a large number of independent, identically distributed (in terms of $\mathbf{H}$) such links, connecting a single base station with multiple MBMS UEs. Namely, we consider a hypothetical scenario where all UEs have similar shadowing with independent fading characteristics. As mention, this scenario is potentially more realistic for large MBMS areas that encompass a large number of evenly distributed base stations.

In the next section we consider different *practical* communication schemes for downlink communication.We compare their spectral efficiency or *achievable rate* R_{target}, for a fixed *outage probability* P_{out}. That is, the achievable rate R_{target} is defined such, that the mutual information between the transmitted signal $\boldsymbol{x}$ and the resulting output of the scheme $\boldsymbol{y}_{\text{eff}}$ for a channel matrix $\mathbf{H}$, denoted by $R_{\text{eff}}(\mathbf{H})$, is lower than R_{target} with probability (over the ensemble of channel matrices)

$$P_{\text{out}} = \Pr(R_{\text{eff}}(\mathbf{H}) < R_{\text{target}}).$$

In parts of this work we shall make use of the following notions of [6]. The *multiplexing gain* or the *pre-log* factor of a scheme is defined as

$$r = \lim_{\rho \to \infty} \frac{E[R_{\text{eff}}(\mathbf{H})]}{\log(\rho)},$$

whereas its diversity gain is defined as

$$d = \lim_{\rho \to \infty} \frac{-\log P_{\text{out}}}{\log(\rho)}.$$

We note that both $E[R_{\text{eff}}(\mathbf{H})]$ and $-\log P_{\text{out}}$ grow with ρ. Furthermore a fundamental tradeoff exists between the two; see [6], [7].

III. Communications Schemes

In this section we consider different practical schemes that employ parallel equal-rate scalar codes, and compare their performance to the optimal theoretical performance (not restricted to equal-rate scalar coding).

A. Optimum Performance

For the Rayleigh fading channel ensemble described in Section II, the optimum performance under individual power constraints are achieved by a white input of per-element unit variance (see, e.g., [8]). Thus, the optimal achievable rate for a specific realization $\mathbf{H}$ is given by

$$R_{\text{opt}}(\mathbf{H}) = \log \left| \mathbf{I} + \mathbf{H}\mathbf{H}^\dagger \right|, \tag{2}$$

where $\mathbf{I}$ denotes the identity matrix, $\dagger$ is the conjugate transpose operation, and $|\mathbf{A}|$ denotes the determinant of $\mathbf{A}$.

In the rest of the section, we restrict attention to the transmission of independent equal-rate scalar streams.

B. Single-Input Multiple-Output Communications

The current LTE standard utilizes only one transmit antenna for MBMS, which corresponds to transmitting only the first entry of $\boldsymbol{x}$. Hence, the equivalent channel is equal to

$$\boldsymbol{y} = \boldsymbol{h}_1 \boldsymbol{x} + \boldsymbol{z},$$

where $\boldsymbol{h}_i$ denotes the i-th column of $\mathbf{H}$.

The optimal receiver in this case reduces to applying maximum-ratio combining (MRC):

$$y_{\text{MRC}} = \boldsymbol{h}_1^\dagger \boldsymbol{y} = \boldsymbol{h}_1^\dagger \boldsymbol{h}_1 \boldsymbol{x} + \boldsymbol{h}_1^\dagger \boldsymbol{z}, \tag{3}$$

which reduces the decoding task to that of scalar decoding.

Thus, the achievable rate of the single-input multiple-output (SIMO) scheme for a given channel matrix $\mathbf{H}$ is[3]

$$R_{\text{SIMO}}(\mathbf{H}) = \log\left(1 + \|\boldsymbol{h}_1\|^2\right). \tag{4}$$

We next consider schemes that employ two transmit antennas.

C. Repetition over Antennas or Transmission within an MBSFN Area

One may consider transmitting the same signal over both transmit antennas, that is,

$$x_1 \equiv x_2 \triangleq x,$$

or equivalently,

$$\boldsymbol{x} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} x.$$

The resulting equivalent channel is

$$\boldsymbol{y} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} x + \boldsymbol{z} \tag{5a}$$

$$= \begin{bmatrix} h_{11} + h_{12} \\ h_{21} + h_{22} \end{bmatrix} x + \boldsymbol{z}. \tag{5b}$$

We note that since the entries of $\mathbf{H}$ are i.i.d. and circularly-symmetric Gaussian, the equivalent channel vector in (5b) is also circularly-symmetric Gaussian with i.i.d. entries with variance 2ρ. This suggests in turn that repetition over the transmit antennas offers no improvement in multiplexing or diversity compared to the SIMO transmission of Section III-C, since the resulting channel is equivalent to (3) up to a 3dB gain in the effective input power (sometimes referred to as ("array gain"). The latter stems from the fact that we consider individual power constraints, and hence the utilization of a second transmit antenna suggests an increase of 3dB in the total power.

We note that this scheme models the current MBMS standard, according to which different base stations (BSs)

[2] This is without loss of generality, as any other constraint can be absorbed in ρ.

[3] All logarithms are taken to base 2 and rates are given in bits.

within the same muticast–broadcast single-frequency network (MBSFN) area transmit the *same* signal. Instead, by viewing this scenario as an effective single BS with multiple antennas (as the transmitted signal is shared by all BSs), performance can be greatly enhanced, as is suggested by the schemes discussed in the sequel.

D. Maximum-Likelihood Decoding

The channel model of (1) under the independent streams constraint reduces to a MIMO multiple-access channel (MAC) [9]. The optimal achievable rate ("sum-rate" in the terminology of MIMO MAC) of a scheme that transmits two independent *equal-rate* streams over the transmit antennas is achieved by ML decoding and is equal to

$$R_{\mathrm{ML}}(\mathbf{H}) = \min \Big\{ C(\mathbf{H}), \; 2\log\left(1+\|\boldsymbol{h}_1\|^2\right), \; 2\log\left(1+\|\boldsymbol{h}_2\|^2\right) \Big\},$$

where the latter two expressions in the minimum are due to the equal-rate constraint and can be regarded as the SIMO achievable rates (4) of each of the two transmit antennas.

We note that ML decoding is computationally expensive and therefore other (suboptimal) decoding processes need to be considered, as discussed further in the next subsection.

Furthermore, we shall see in Sections III-F and III-G, that by applying linear precoding to the transmitted equal-rate streams across several time instants, i.e., by incorporating space–time coding (STC), a rate close to $C(\mathbf{H})$ can be achieved, which outperforms R_{ML}. Using ML decoding for these STC structures has much higher computational complexity which calls for employing other decoding methods.

E. Integer-Forcing Decoding

Due to the high complexity of the ML decoder, a suboptimal lattice-based scheme was proposed, with decoding complexity that is similar to that of single-stream decoding, which decodes (linearly independent) integer combinations of the lattice codewords, and then recovers the transmitted codewords from these combinations. For details, see [10], [11].

We next recall the achievable rate of this scheme. To this end, define the real representation of the complex-valued channel matrix $\mathbf{H}$:

$$\mathbf{H}_{\mathrm{real}} \triangleq \begin{bmatrix} \Re\{\mathbf{H}\} & -\Im\{\mathbf{H}\} \\ \Im\{\mathbf{H}\} & \Re\{\mathbf{H}\} \end{bmatrix},$$

where $\Re\{\mathbf{H}\}$ and $\Im\{\mathbf{H}\}$ denote the real and imaginary parts of $\mathbf{H}$, respectively. For a 4×4 integer matrix $\mathbf{A}$, denote by $\mathbf{L}$ the lower-triangular matrix resulting after applying the Cholesky decomposition to

$$\mathbf{A}\left(\mathbf{I}+\mathbf{H}_{\mathrm{real}}\mathbf{H}_{\mathrm{real}}^{\dagger}\right)^{-1}\mathbf{A}^T = \mathbf{L}\mathbf{L}^T.$$

Then, the achievable rate of this scheme is given by

$$R_{\mathrm{IF}} = -2\log \min_{\mathbf{A}} \max_{i=1,\dots,4} \ell_i^2,$$

where $\mathbf{A}\in\mathbb{Z}^{4\times 4}$ and ℓ_i is the i-th diagonal value of $\mathbf{L}$.

F. Alamouti's Orthogonal Space–Time Block Code

For multiple-input single-output (MISO) 2×1 channels, the Alamouti orthogonal space–time block code (OSTBC)[4] [5] is known to achieve (2) using equal-rate scalar codes via a suitable orthogonal design:

$$\begin{bmatrix} \boldsymbol{x}[1] & \boldsymbol{x}[2] \end{bmatrix} = \begin{bmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{bmatrix}, \tag{6}$$

where c_1 and c_2 are the two scalar (equal-rate independent) codewords transmitted across the effective scalar channels. Note that $\boldsymbol{x}[1]$ and $\boldsymbol{x}[2]$ are orthogonal in this case, which translates to independence if Gaussian codebooks c_1 and c_2 are used.

For 2×2 channels, Alamouti's OSTBC (6) can be rewritten in the following equivalent way:

$$\begin{bmatrix} \boldsymbol{y}[1] \\ \boldsymbol{y}[2] \end{bmatrix} = \begin{bmatrix} \mathbf{H} & \mathbf{0} \\ \mathbf{0} & \mathbf{H} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}[1] \\ \boldsymbol{x}[2] \end{bmatrix} + \begin{bmatrix} \boldsymbol{z}[1] \\ \boldsymbol{z}[2] \end{bmatrix},$$

where $\mathbf{0}$ denotes an all-zero matrix, and $\boldsymbol{z}[1]$, $\boldsymbol{z}[2]$ are the noise vectors at time index 1 and 2, respectively.

By substituting (6), this can be further re-written as

$$\boldsymbol{y}_{\mathrm{Alamouti}} = \mathbf{H}_{\mathrm{Alamouti}}\boldsymbol{c}_{\mathrm{Alamouti}} + \boldsymbol{z}_{\mathrm{Alamouti}},$$

where

$$\boldsymbol{y}_{\mathrm{Alamouti}} \triangleq \begin{bmatrix} \boldsymbol{y}[1] \\ \boldsymbol{y}^*[2] \end{bmatrix}, \quad \boldsymbol{c}_{\mathrm{Alamouti}} \triangleq \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}, \quad \boldsymbol{z}_{\mathrm{Alamouti}} \triangleq \begin{bmatrix} \boldsymbol{z}[1] \\ \boldsymbol{z}^*[2] \end{bmatrix},$$

$$\mathbf{H}_{\mathrm{Alamouti}} \triangleq \begin{bmatrix} \mathbf{H} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}^* \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & -1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix}.$$

As in MISO case, the orthogonality of the columns of $\mathbf{H}_{\mathrm{Alamouti}}$ implies that the codewords c_1 and c_2 pass effectively through parallel SIMO channels. Moreover, note that each of these columns has the same norm which is equal to the Frobenius norm of the physical channel matrix $\mathbf{H}$ and is defined as $\|\mathbf{H}\|_F^2 = \sum_{i,j}|h_{ij}|^2$. Thus, by applying MRC at the receiver, the following rate is achieved

$$R_{\mathrm{Alamouti}} = \log\left(1+\|\mathbf{H}\|_F^2\right).$$

We note that the pre-log factor is 1 since normalization by the number of physical channel uses, which is equal to 2 in this case, needs to be performed.

[4]In the context of this paper, OSBTCs should be treated as modulations rather than codes.

This technique achieves full diversity, but does not allow to achieve beyond half of the possible multiplexing gain [6]. Namely, its pre-log factor is equal to 1, in contrast to the optimal possible 2.

G. Non-Orthogonal Space–Time Modulations

To allow higher multiplexing gains a *multi-layer Alamouti* (MLA) scheme was proposed in [12]. In this scheme, the transmitter sends two layers of codes precoded using the Alamouti OSTBC, with a phase difference of $\pi/2$ radians between the two:

$$\begin{aligned}\begin{bmatrix}\boldsymbol{x}[1] & \boldsymbol{x}[2]\end{bmatrix} &= \begin{bmatrix} c_1 & -c_3^* \\ c_3 & c_1^* \end{bmatrix} + \begin{bmatrix} c_2 & c_4^* \\ c_4 & -c_2^* \end{bmatrix} \\ &= \begin{bmatrix} c_1 + c_2 & c_4^* - c_3^* \\ c_3 + c_4 & c_1^* - c_2^* \end{bmatrix}. \end{aligned} \tag{7}$$

For the 2×2 MIMO case of Section II, the resulting channel output can be written as

$$\begin{bmatrix}\boldsymbol{y}[1] \\ \boldsymbol{y}[2]\end{bmatrix} = \begin{bmatrix}\mathbf{H} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}\end{bmatrix}\begin{bmatrix}\boldsymbol{x}[1] \\ \boldsymbol{x}[2]\end{bmatrix} + \begin{bmatrix}\boldsymbol{z}[1] \\ \boldsymbol{z}[2]\end{bmatrix},$$

where $\boldsymbol{z}[1]$, $\boldsymbol{z}[2]$ are the noise vectors at time index 1 and 2, respectively. By substituting (7) this can be re-written as

$$\boldsymbol{y}_{\mathrm{MLA}} = \mathbf{H}_{\mathrm{MLA}} \boldsymbol{c}_{\mathrm{MLA}} + \boldsymbol{z}_{\mathrm{MLA}}, \tag{8}$$

where

$$\boldsymbol{y}_{\mathrm{MLA}} \triangleq \begin{bmatrix}\boldsymbol{y}[1] \\ \boldsymbol{y}^*[2]\end{bmatrix},$$

$$\boldsymbol{z}_{\mathrm{MLA}} \triangleq \begin{bmatrix}\boldsymbol{z}[1] \\ \boldsymbol{z}^*[2]\end{bmatrix},$$

$$\boldsymbol{c}_{\mathrm{MLA}} \triangleq \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix},$$

$$\begin{aligned}\mathbf{H}_{\mathrm{MLA}} &\triangleq \begin{bmatrix}\mathbf{H} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}^*\end{bmatrix}\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & 1 \\ 1 & 0 & -1 & 0 \end{bmatrix} \\ &= \begin{bmatrix} h_{11} & h_{12} & h_{11} & h_{12} \\ h_{21} & h_{22} & h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* & -h_{12}^* & h_{11}^* \\ h_{22}^* & -h_{21}^* & -h_{22}^* & h_{21}^* \end{bmatrix}.\end{aligned}$$

We note that, in contrast to the single-layer Alamouti scheme of Section III-F, the columns of the effective channel matrix $\mathbf{H}_{\mathrm{MLA}}$ are no longer orthogonal, i.e., separate decoding of each of the codewords c_i ($i = 1, 2, 3, 4$) is suboptimal and joint decoding is necessary to achieve optimum performance. Nevertheless, each column is orthogonal to one additional column, which may facilitate in reducing the complexity of joint (ML) decoding [13]. The MLA scheme allows to achieve the following rate (under ML decoding):

$$R_{\mathrm{MLA}} = \frac{1}{2} \log \left| \mathbf{I} + \mathbf{H}_{\mathrm{MLA}} \mathbf{H}_{\mathrm{MLA}}^{\dagger} \right|,$$

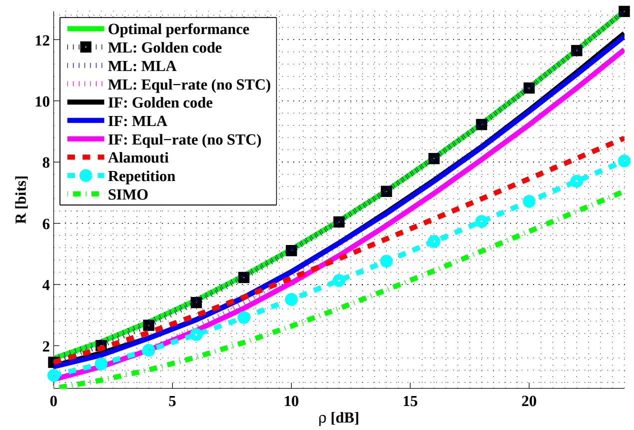

Fig. 1. Achievable rates for an outage probability of 0.01.

where the pre-log factor is $1/2$ due to the normalization by the number of time instants utilized for each effective channel use (8).

Since this scheme can achieve multiplexing gains larger than 1, it outperforms the classical Almaouti OSTBC considered in Section III-F for high SNRs (see Fig. 1). However, this scheme does not attain the optimal diversity–multiplexing tradeoff (DMT) curve [14]. In fact, this scheme can be regarded as an approximated variant of the *golden code* [15]–[18], which was designed to attain the optimal DMT curve [6]. The performance of both of these schemes under ML and IF decoding are depicted in Fig. 1.

IV. Numerical Performance Evaluation

In this section we evaluate the achievable rates of the different schemes of Section III for a fixed outage probability. Namely, we calculate the achievable rates of the previous section for a large ensemble of channel realizations, and take the P_{out} percentile.

Consider the achievable rates for an outage probability of $P_{\mathrm{out}} = 0.01$, depicted in Fig. 1.

First note that the rate penalty due to equal-rate constraint for each of the streams, is very modest at low SNRs and vanishes for higher SNRs, when using the space–time transmitters of Section III-G. Unfortunately, IF decoding incurs substantial losses compared to these performance (achieved by ML decoding).

Interestingly, for two transmit antennas, Alamouti OSTBC performs quite well for typical SNR values, and improves by more than 1 bit/sec/Hz for signal-to-noise ratio of 10dB or higher.

We note that for higher outage probabilities the IF-based techniques outperform the Alamouti OSTBC already at lower SNR values, as is evident from Fig. 2.

Remark 1: We refer the reader to [19] for the dual diversity-order evaluation of some of the schemes of Section III.

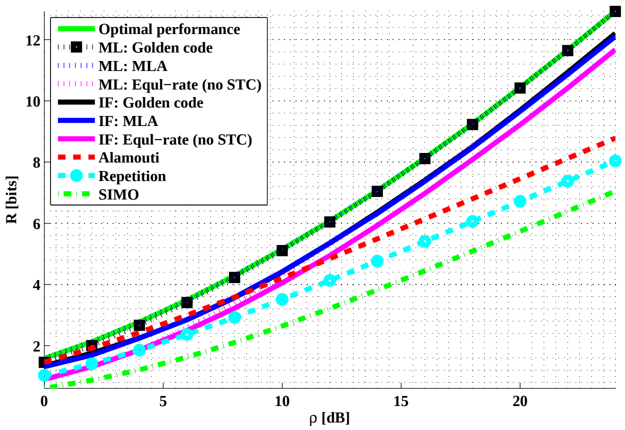

Fig. 2. Achievable rates for an outage probability of 0.1.

V. Discussion and Further Work

In this work we demonstrated the advantages of working with multiple antennas at the transmitter. Moreover, space–time modulation structures were shown to attain further enhancement in performance. Specifically, we observed that Alamouti OSTBC attains good performance for two antennas. Unfortunately, for more than two transmit antennas, Alamouti is far away from optimality and non-orthogonal space–time modulation structures, as in Section III-G, need to be considered.

We also note that we assumed the same channel characteristics for all users and an open-loop scenario. In practice, the channel characteristics of various users may differ due to e.g., shadowing or near–far scenarios. Moreover, in the LTE standard a small amount of feedback is available for conveying to the transmitter the rate supported by each of the user. The performance of this "rate-aware" scenario can be evaluated in a similar fashion to the setting of this paper, by considering ensembles of channel matrix possessing mutual information that is bounded from below and evaluating the achievable rate of each of the schemes of Section III. Moreover, by considering ensembles with various characteristics (e.g. not necessarily Rayleigh) more realistic settings can be addressed.

References

[1] "Connected future of connected cars: Trends of 2015." [Online]. Available: http://www.startupbootcamp.org/blog/2015/february/connected-future-of-connected-cars-trends-of-2015.html

[2] J. Calabuig, J. F. Monserrat, D. Gozalvez, and O. Klemp, "Safety on the roads: LTE alternatives for sending ITS messages," vol. 9, no. 4, pp. 61–70, Dec. 2014.

[3] "Study on LTE support for V2X services, SID S1-150238," *3GPP TSG-SA WG1 Meeting #69*, Feb. 2015.

[4] "Multimedia broadcast multicast services: Architecture and functional description," *3GPP TS Standard 23.246 V11.1.0*, March 2012.

[5] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Selected Areas in Comm.*, vol. 16, pp. 1451–1458, Oct. 1998.

[6] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Info. Theory*, vol. 49, pp. 1073–1096, May 2003.

[7] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. U.K: Cambridge Univ. Press, 2005.

[8] M. Katz and S. Shamai, "On the outage probability in multiple antenna systems," *IEEE Trans. Wireless Comm.*, vol. 6, pp. 4120–4128, 2007.

[9] W. Yu, "Competition and cooperation in multi-user communication environments," Ph.D. dissertation, Stanford University, 2002.

[10] J. Zhan, B. Nazer, U. Erez, and M. Gastpar, "Integer-forcing linear receivers," *IEEE Trans. Info. Theory*, vol. 60, pp. 7661–7685, 2014.

[11] J. Zhan, B. Nazer, O. Ordentlich, U. Erez, and M. Gastpar, "Integer-forcing architectures for MIMO: Distributed implementation and SIC," Nov. 2010, pp. 322–326.

[12] U. Eachsmann, J. Thilecke, and H. Schotten, "Exploiting the data-rate potential of MIMO channels: Multi-stratum space–time coding," vol. 1, May 2001, pp. 199–203.

[13] S. Sezginer and H. Sari, "A high-rate full-diversity $2x2$ space–time code with simple maximum likelihood decoding," in *Proc. IEEE Int. Symp. on Sig. Proc. and Info. Tech. (ISSPIT)*, Cairo, Egypt, Dec. 2007, pp. 1132–1136.

[14] U. Erez, "Private communication."

[15] H. Yao and G. W. Wornell, "Achieving the full MIMO diversity–multiplexing frontier with rotation-based space-time codes," in *Proc. Annual Allerton Conf. on Comm., Control, and Comput.*, Monticello, IL, USA, Oct. 2003, pp. 400–409.

[16] J.-C. Belfiore, G. Rekaya, and E. Viterbo, "The golden code: A 2×2 full-rate space–time code with nonvanishing determinants," *IEEE Trans. Info. Theory*, vol. 51, pp. 1432–1436, 2005.

[17] F. Oggier, G. Rekaya, J.-C. Belfiore, and E. Viterbo, "Perfect space–time block codes," *IEEE Trans. Info. Theory*, vol. 52, pp. 3885–3902, 2006.

[18] P. Elia, B. A. Sethuraman, and P. V. Kumar, "Perfect space–time codes for any number of antennas," *IEEE Trans. Info. Theory*, vol. 53, pp. 3853–3868, 2007.

[19] W. Domanovitz and U. Erez, "Combining space-time block modulation with integer forcing receivers," in *Proc. IEEE 27th Convention of Electrical and Electronics Engineers in Israel (IEEEI)*, Eilat, Israel, Nov. 2012.