Performance Evaluation of Media-based Modulation in Comparison with Spatial Modulation and Legacy SISO/MIMO

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***Abstract*—The idea of Media-based Modulation (MBM), introduced in [1] [2], is based on embedding information in the variations of the transmission media (channel states). This is in contrast to legacy wireless systems (called Signal-Based Modulation, SBM, in current article) where data is embedded in a Radio-Frequency (RF) source prior to the transmit antenna. MBM offers several advantages vs. legacy systems, including "additivity of information over multiple receive antennas", and "inherent diversity over a static fading channel". MBM is particularly suitable for transmitting high data rates using a single transmit and multiple receive antennas (Single Input-Multiple Output Media-Based Modulation, or SIMO-MBM). Furthermore, to address complexity issues (hardware and algorithmic complexities, as well as the training overhead) that limit the amount of data that can be embedded in channel states using a single transmit unit, Layered Multiple Input-Multiple Output Media-Based Modulation (LMIMO-MBM) is introduced in [3]. Current articles compares performance of MBM and LMIMO-MBM vs. legacy Multiple Input-Multiple Output (MIMO), and a recently introduced modulation scheme called Spatial Modulation (SM) and its generalization called Generalized Spatial Modulation (GSM). These comparisons demonstrate significant performance gains for MBM and LMIMO-MBM vs. these known techniques.**

I. Introduction

Shannon capacity results indicate that the transmission rate can increase as a linear function of the available spectrum, multiplied by a logarithmic function of the transmit energy. Wireless communications relies on two key attributes, which are also traditionally considered at its inherent bottlenecks. First, the spectrum is shared, resulting in mutual interference among wireless links operating over the same spectrum. Second, transmission channel includes a multitude of propagation paths, resulting in multi-path fading. Multi-path fading in turn can result in deep fades when signals received through different transmission paths add destructively. In many scenarios of practical interest, the transmission paths change only slowly with time (slow fading), potentially resulting in a long lasting degradation of the received Signal-to-Noise-Ratio (SNR), referred to as deep fades.

Multiple-Input Multiple-Output (MIMO) antenna systems embrace the above two attributes towards improving the spectrum/power efficiency [4][5][6], as well as in dealing with deep fades [7]. It is also known that, to combat slow fading, the degrees of freedom offered by MIMO systems can be used to create diversity. Diversity order, which in essence captures the number of independent paths (independent gains) involved in the end-to-end transmission, can be increased, but only at the cost of a reduction in Multiplexing Gain (MG) [8].

Although MIMO systems provide an elegant way to tailor wireless communications to adopt to its two fundamental attributes/bottlenecks mentioned earlier, three issues limit their achievable rate vs. energy. First, the problem of deep fades still exists and can be only (partially) alleviated at the cost of a reduction in the achievable rate (MG) [8]. Second, MG increases only with the smaller of the number of transmit and receive antennas. Third, the MIMO channel matrix is typically non-orthogonal, reducing the achievable rate as compared to an orthogonal channel matrix with a similar dimensionality. Media-based Modulation (MBM) deals with these three issues. The core idea is based on randomizing the wireless channel through perturbing the propagation environment in the vicinity of transmit antenna(s), which in turn will change the overall transmission path. This can be viewed as creating a multitude of channel states, each corresponding to a different transmission path, where the transmitter can select any of the channel states in each transmission. The information to be transmitted is used by the transmitter as an index to select a particular channel state.

Example: Consider a wireless channel with two states s_1 and s_2. In one of the states, the channel gain is equal to 0.5, and in the other state, it is equal to 1.5. Transmitter can select either of the two states in each transmission, but is not aware of the correspondence of the two gain values to the two states (does now know which state corresponds to which gain value). Let us assume we are interested in transmitting two bits per channel use. In one scenario, reminiscent of SBM, the transmitter selects one of the two states for all its transmissions and use it with a Pulse-Amplitude-Modulation (PAM) constellation of size 4, composed of points $\{-3,-1,1,3\}$. With probability $1/2$, the selected channel state corresponds to the one with the lower gain, resulting in the received constellation being composed of points $\mathcal{C}_1 = \{-3/2,-1/2,1/2,3/2\}$ with a $d_{\min} = 1$. This means one can guarantee a worst case $d\text{min}$ equal to 1 using an average transmit energy of $(9+1+1+9)/4 = 5$. In a second scenario, reminiscent of MBM, for each transmission, transmitter uses one bit of information to select the channel state, and transmits a Binary-Phase-Shift-Keying (BPSK) modulation with points $\{-1,1\}$ through the selected state. It easily follows that the receiver will observe a 4-PAM constellation with points $\mathcal{C}_2 = \{-3/2,-1/2,1/2,3/2\}$, again resulting in $d_{\min} = 1$, but this time at the cost of using one unit of energy vs. the 5 units used in the first scenario. The underlying assumption is that, although transmitter is oblivious to the actual realization of the channel gain, receiver is aware of the structure of the constellation and its labelling. This information can be easily conveyed to the receiver through an initial training phase, in which the transmitter selects the two channel states in an order that is prearranged with the receiver.

The above example shows another notable property. If the channel state is changed randomly from transmission to transmission, the equivalent channel can become Ergodic in time. In other words, the better and the worse channel states collectively contribute to constructing a single constellation, which will be in effect in all transmissions. This case corresponds to constellation $\mathcal{C}_2$ in this example. As a consequence, the inherent bottleneck occurring in the case of SBM, corresponding to being stuck with the worse channel state in all transmissions is avoided. This phenomenon is interpreted as an inherent (built-in) diversity effect. Reference [2] shows that, this phenomenon will asymptotically (for large constellation sizes) convert a static fading channel into an (Ergodic) AWGN channel. This is unlike traditional MIMO systems where an increase in the diversity order is unavoidably accompanied by a reduction in rate (MG). ■

A. Literature Survey

Reference [1] shows that embedding part or all of the information in the (intentional) variations of the transmission media (channel states) can offer significant performance gains vs. traditional Single-Input Single-Output (SISO), Single-Input Multiple-Output (SIMO) and Multiple-Input Multiple-Output (MIMO) systems. This method, coined in [1] as Media-Based Modulation (MBM), is in contrast with traditional wireless systems where data is embedded in the variations of an RF source (prior to the transmit antenna) to propagate via fixed propagation paths (media) to the destination. In particular, using capacity arguments, reference [1] shows that by using a single transmit antenna and a single or multiple receive antennas; MBM can significantly outperform SBM.

Following [1], reference [2] proves that, a $1 \times K$ MBM over a static multi-path channel asymptotically achieves the capacity of K (complex) AWGN channels, where for each unit of energy over the single transmit antenna, the effective energy for each of the K AWGN channels is the statistical average of channel fading. In addition, the rate of convergence is computed. It is shown that significant gains can be realized even in a SISO-MBM setup. An example for the practical realization of the system using RF mirrors, accompanied with realistic RF and ray tracing simulations, are presented. Issues of equalization and selection gain are also briefly discussed.

There have been some recent works on embedding data in antenna beam-patterns [9]-[11] or antenna selection [12]-[16]. Note that unlike MBM, none of these works can realize advantages due to embedding information in the channel state. Most notably, these advantages, reported for the first time in [1] [2], include "additivity of information over multiple receive antennas" and "inherent diversity without sacrificing transmission rate". In [9] [10], data is embedded in two orthogonal antenna beam-patterns, which can transmit a binary signal set. Although use of orthogonal basis is common in various formulations involving communications systems, it usually does not bring any benefits on its own, it just simplifies problem formulation and signal detection by keeping the noise projections uncorrelated. This means there are no clear advantages in designing the RF front-end to support orthogonal patterns as used in [9] [10]. The motivation in [9] [10] is to reduce the number of transmit chains and no other benefits are discussed. Bains [11] discusses using parasitic elements for data modulation, and shows limited energy saving, which again is due to the effect of classical RF beam-forming.

Spatial Modulation (SM) [12]-[16] uses multiple transmit antennas with a single RF chain, where a single transmit antenna is selected according to the input data (the rest of the data modulates the signal transmitted through the selected antenna). SM is in essence a diagonal space-time code, where the trade-off between diversity and multiplexing gain has been in favour of the latter. A shortcoming of SM is that the rate due to the spatial portion increases with $\log_2$ of the number of antennas, while in MBM, it increases linearly with the number of RF mirrors (on-off RF mirrors are introduced in [2] as means of embedding binary data in the channel state). In SM, antennas should be sufficiently separated to have independent fading, while in MBM, RF mirrors are placed side by side. The switches used in SM are high power, which means expensive/slow, or each antenna needs a separate Power Amplifier (PA) with switches placed before PAs. The switches used for RF mirrors in MBM are cheap, low power and fast. In continuation to SM, which uses a single RF chain, references [17]— [19] propose a generalization to SM, called Generalized Spatial Modulation (GSM) hereafter, based on activating more than one antenna to embed information. This results in improved performance at the cost of using more than a single RF chain. The use of tunable parasitic elements external to the antenna(s) for the purpose of RF beam-forming is well established. However, the objective in traditional RF beam-forming is "to focus/steer the energy beam, which does not realize the advantages of MBM (where data is modulated by tuning external parasitic elements).

The advantages of MBM, are discussed in further details in [1][2].

II. Comparison with Spatial Modulation (SM), Generalized Spatial Modulation (GSM) and Legacy SISO/SIMO/MIMO

To have a more than fair comparison between Media-Based wireless with legacy MIMO systems in a static Rayleigh fading channel, outage capacity performances of different legacy MIMO systems are measured against Symbol Error Rate (SER) of an MBM system. In addition, capacity curves for MBM based on using a single transmit antenna are presented. Note that using multiple

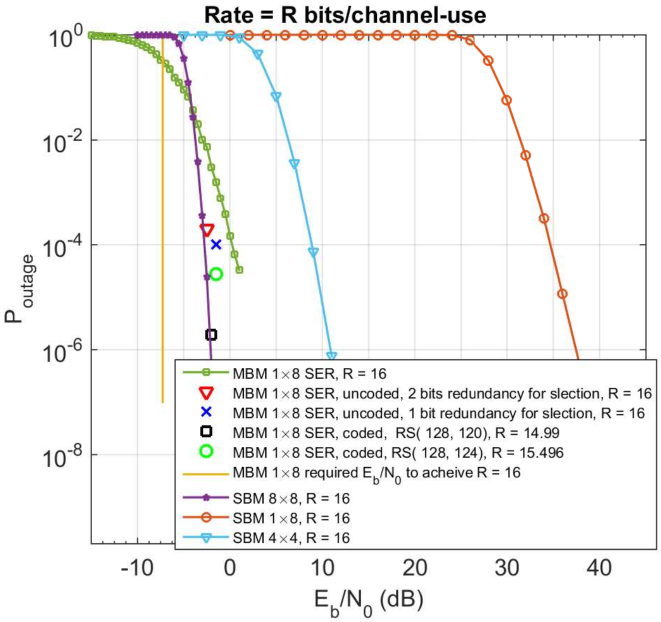

Fig. 1: Comparison of 1×8 MBM (Media-based Modulation) vs. 4×4 and 1×8 SBM (Source-Based Modulation) for rates around 16 bits/sec/Hz. Note that legacy SBM performance is expressed in terms of outage capacity (implicitly relying on optimum channel coding), while MBM performance (point specified by $\times$) is raw (un-coded) symbol error rate.

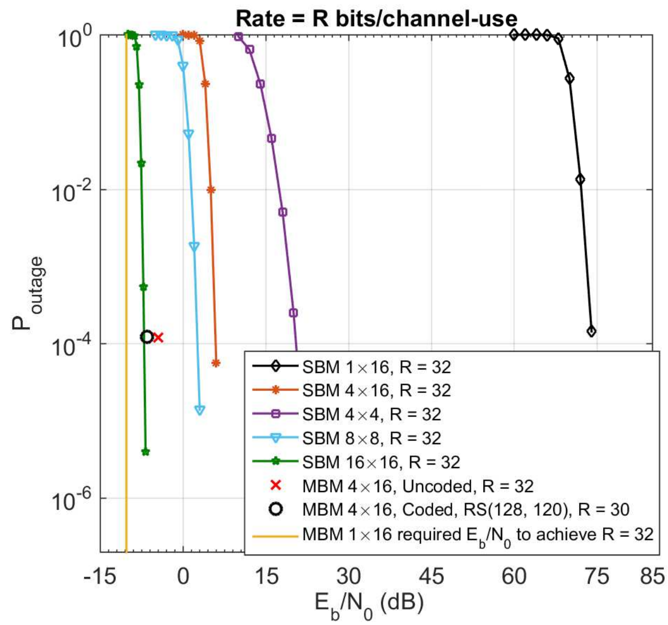

Fig. 2: Comparison of 1×16 MBM (Media-based Modulation) and its reduced complexity implementation (with inferior performance) in the form of 4×16 Layered MIMO-MBM vs. 1×16, 4×16, 4×4, 8×8, and 16×16 SBM (Source-Based Modulation) for rates around 32 bits/sec/Hz. Note that legacy SBM performance is expressed in terms of outage capacity (implicitly relying on optimum channel coding), while MBM performance (point specified by $\times$) is raw (un-coded) symbol error rate.

transmit antenna in Layered MIMO-MBM merely helps in reducing system complexity (in terms of both implementation and maing simulations tractable), and the performances reported for Layered MIMO-MBM are inferior to what can be achieved using MBM alone (i.e., MBM with a single transmit antenna). Figure 1 compares a 1×8 MBM vs. 4×4 and 1×8 legacy SBM (legacy MIMO) for rates around 16 bits/sec/Hz. Figure 2 compares a 1×16 MBM and its reduced complexity implementation (with inferior performance) in the form of 4×16 Layered MIMO-MBM vs. 1×16, 4×16, 4×4, 8×8, and 16×16 SBM for rates around 32 bits/sec/Hz. The solid lines with no marker in the two figures indicate the required E_b/N_0 to achieve the corresponding rates (16 bits/sec/Hz and 32 bits/sec/Hz), according to MBM capacity expressions provided in [1], [2]. It is observed that MBM results in significant saving in energy, even in comparing a $1 \times K$ MBM to a $K \times K$ MIMO.

Figure 3 compares outage capacities curves in the case of SISO for rates 3, 5 and 7 bits/sec/HZ. The outage probabilities for SISO-MBM is calculated using the mutual information corresponding to different realizations of an MBM constellation. Number of points in the constellations used to calculate MBM outage probabilities are 64 (corresponding to 6 RF mirrors), 256 (corresponding to 8 RF mirrors) and 512 (corresponding to 9 RF mirrors) for rates 3, 5 and 7 bits/sec/HZ, respectively. This means, rates 3,5,7 are achieved relying on a redundancy of 3,3 and 2 bits, respec-

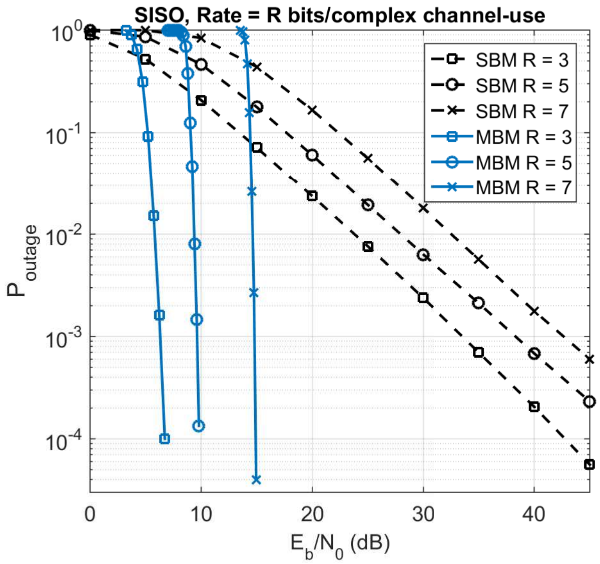

Fig. 3: Comparison (in terms of outage probability) of 1×1 (SISO) MBM (Media-based Modulation) vs. legacy 1×1 (SISO) SBM (Source-based Modulation) for rates of 3,5,7 bits/sec/Hz.

tively. It is observed that performance gains are particularity pronounced in SISO setups due to inherent diversity of MBM.

Tables I and II provide a comparison between MBM and Spatial Modulation (SM) and Generalized Spatial Modulation (GSM) for rates of 6 bits/sec/HZ and 9 bits/sec/HZ. Performance of SM and GSM are extracted from reference [18], [19] after converting the energy axis from Signal-to-Noise-Ratio (used in [18], [19]) to E_b/N_0 for consistency. Tables show significant performance gains for MBM vs. SM and GSM. It is should be mentioned that the advantages of MBM become more evident at higher values of spectral efficiency, while the vast majority of results reported in the literature for SM and GSM are for lower rates. The comparisons provided in tables I and II rely on low spectral efficiencies (suitable for SM and GSM). In other words, for higher spectral efficiency values, the improvements due to MBM vs. SM and GSM would be significantly higher than what is observed in tables I and II. To clarify this point, table I which is provided to compare MBM vs. SM and GSM for 8 bits/sec/HZ, also include the performance of MBM for 16 bits/sec/HZ. It is observed that increasing the rate of MBM from 8 bits/sec/HZ to 16 bits/sec/HZ is achieved at the cost of a small (about 1dB) increase in E_b/N_0.

Tables I and II are based on average (uncoded) error rates. Another factor relevant to this comparison is the standard deviation of such average error values, which provides an indication of the “diversity order. This is also reflected in the slope of error curves vs. SNR. In MBM, diversity is inherent, and improves with the number of constellation points, providing steeper slopes for the error curves of MBM vs. that of SM and GSM. Readers can compare the slope of error curves corresponding to SM, GSM, reported in the literature on SM/GSM (e.g., reference [19]), with those presented in the current article. Such a comparison is not provided here, as it depends on the rate/number of antennas, and is beyond the scope of the current article.

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TABLE I: Performance of MBM (Media-based Modulation) vs. SM (Spatial Modulation) and GSM (Generalized Spatial Modulation) for a rate of 6 bits/channel use (extracted from [18], [19]). Note the rows specified by $\star$ show that MBM is capable of sending a significantly higher number of bits (16 bits vs. 8 bits) at a marginally higher E_b/N_0 (at an increase of 0.8dB for Error Rate of 10^{-3} and 1.25dB for Error Rate of 10^{-4}). References [18], [19] are used for the purpose of comparison as other articles devote to SM either: (1) rely on fading models, such as Rician, that would not be suitable for comparison with MBM (MBM results rely on static Rayleigh fading), or (2) the rates per channel and/or the number of antennas would not be comparable.

Number of TX Antennas	Number of RX Antennas	Rate in bits/sec/Hz	Error Rate	Method	E_b/N_0 in dB	Relative Gain of MBM	
1	8	6	10^{-3}	MBM	-2	-	
8	8	6	10^{-3}	SM	25	27 dB	
5	8	6	10^{-3}	GSM	8	10 dB	
1	8	16	10^{-3}	MBM	-1.2	-	$\star$
1	8	6	10^{-4}	MBM	-1	-	
8	8	6	10^{-4}	SM	37	38 dB	
5	8	6	10^{-4}	GSM	10	11 dB	
1	8	16	10^{-4}	MBM	0.25	-	$\star$

TABLE II: Performance of MBM (Media-based Modulation) vs. GSM (Generalized Spatial Modulation) for a rate of 9 bits/channel use.

Number of TX Antennas	Number of RX Antennas	Rate in bits/sec/Hz	Error Rate	Method	E_b/N_0 in dB	Relative Gain of MBM
1	6	9	10^{-3}	MBM	1	-
5	6	9	10^{-3}	GSM	17.5	16.5 dB
1	6	9	10^{-4}	MBM	2.5	-
5	6	9	10^{-4}	GSM	22.5	20 dB

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