Hybrid Selection/MRC for DVB-S2/RCS in Land Mobile Satellite Scenarios

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In this paper, we propose a multi-antenna technique to improve the link reliability of a satellite communications system. More specifically, we consider a railway scenario where performance is considerably affected by periodic fading associated with power supply arches and tunnels. In order to optimize system performance in terms of SER and spectral efficiency, we adopt a reception strategy based on the Hybrid Selection/MRC approach. This technique consists in activating only the best sub-set of L antennas out of a total number of N antennas ($L < N$). By doing so, diversity gains offered by an N antenna system can be exploited but only L complete RF chains are required. Algorithm performance is compared with that obtained with several schemes exploiting spatial diversity in a different way. Finally, we derive a simplified version of the Hybrid Selection/MRC approach, where a lower number of antenna sub-sets are considered in the selection procedure. Computer simulation results show that most of the gains obtained with the full antenna system can be extracted with the proposed reduced complexity approach.

I. Introduction

New satellite communications systems are expected to provide broadband services to mobile users terminals. In order to take advantage of the current technology, it is of great interest to study the viability of adopting the DVB-S2 standard[1] in a land mobile satellite (LMS) scenario, where some problems appear due to the mobility as the Doppler effect, the possible loss of the line-of-sight and the time-variant nature of the channel.

Antenna diversity has been already proposed as a powerful fade mitigation mechanism for a LMS scenario in previous studies[2,3]. Specifically, the railway scenario was addressed where, apart from the increased variability of the channel, a periodic fading event is observed associated with the power supply arches. Moreover, the apparition of several tunnels during the journey is an issue to consider. In the paper by Cioni *et al.*,[2] the authors showed that by placing two antennas with an adequate separation, the fading corresponding to the power supply arches can be completely compensated. However, antenna separation must be carefully chosen when the tunnel fading is considered. For instance, if the two antennas are placed at the beginning and at the end of the train, respectively, the power arches fading can only be partially compensated (one of two antennas becomes inefficient when the train enters/exits the tunnel) Nonetheless, the tunnel fading effect is efficiently alleviated in those situations where the tunnel length is not much higher than the train one. An alternative to combat both effects is the use of time diversity[3] (i.e., by sending replicas of the same packet in different time instants) but transmission efficiency is lost by sending redundant versions of the packet.

In this paper, we focus on the spatial diversity concept and propose a hybrid selection/Maximal-Ratio Combining (MRC) strategy. First, the best sub-set of two out of four receive antennas is selected for reception. After that, the received signals are combined by means of a MRC procedure. This scheme was shown to be very effective in wireless networks as most of the diversity gain obtained with the full antenna system can be extracted but only two complete RF chains are needed and, thus, receiver complexity and hardware cost are not substantially increased[4]. In the railway scenario, the main idea consists in placing

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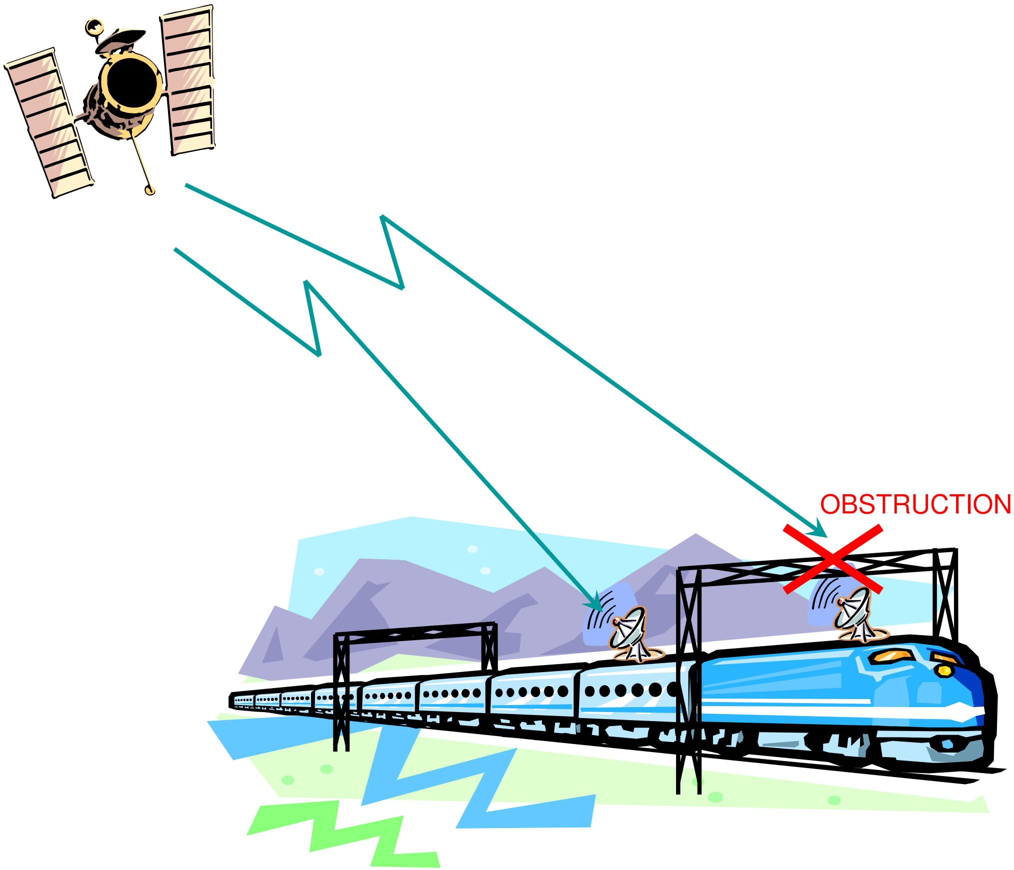


Figure 1. Satellite communication link in a railway scenario.

groups of two antennas at the beginning and at the end of the train, respectively. The receiver adaptively selects the best sub-set of two antennas and, by doing so, the system is effective for compensating both the power supply arches and tunnel fading effects. Differently from the time diversity scheme, spectral efficiency is not lost. Besides, the reliability of the channel is quite improved as the system is able to select out of four different diversity branches. In this paper we consider scenarios corresponding to Italian railway networks, for which performance is assessed in terms of Symbol Error Rate (SER) and spectral efficiency metrics. As simulation results show, our methodology considerably improves system performance while keeping a reduced hardware complexity.

The remainder of the paper is organized as follows. The corresponding signal and system model is presented in Section II. Next, we introduce the Hybrid Selection/MRC strategy in detail in Section III. After that, we present the reception schemes taken into consideration in our analysis in Section IV. Simulation results are discussed in Section V and, finally, we close the paper with the conclusions section.

II. Signal and System Model

Consider the forward link of a railway scenario as represented in Fig. 1. In the proposed scenario, a satellite communications system based on DVB-S2 standard[1] provides broadband services to high-speed trains. In such a scenario, the channel response can be modelled by the superposition of a three-state Markov-Chain channel model (see Table 1) and a periodic fading event[3]. Such a periodic event is associated with periodic obstructions of the signal caused by the power supply arches (see Fig. 1), producing attenuations

Table 1. Three states channel description.

State	Description	Characteristics
LOS	Line-of-Sight	Rice distribution, K=17dB
NLOS	Shadowing due to single trees	RLN distribution: • Small Scale Fading → Rice, K=0 dB • Large Scale Fading → Lognormal
Blockage	Blockages due to buildings, bridges and tunnels	No signal received

of approximately 15 dB with fade widths of the order of 0.5 and 1 m.

In order to improve link reliability, a multiple-antenna system is adopted at the receiver (i.e., at the high-speed train). By doing so, the negative effects associated to the LMS channel are alleviated by antenna diversity gains. Besides, the obstruction caused by the power supply arches are compensated. This can be easily done by carefully separating receive antennas in such a way that simultaneous obstructions are avoided.

In a multiple antenna system, the base band signal received at any time instant can be modelled in vectorial form as:

$$\mathbf{r} = \mathbf{h}s + \mathbf{n} \tag{1}$$

where the time index have been dropped for the ease of notation, $\mathbf{h} \in \mathbb{C}^{N\times 1}$ is the channel vector associated to the railway channel, N is the number of receive antennas, $s \in \mathbb{C}$ denotes the transmitted symbol with average transmitted power P drawn out of the constellation selected by the adaptive modulation mechanism[1], and $\mathbf{n} \in \mathbb{C}^{N\times 1}$ stands for an additive Gaussian noise vector of complex, random variables with zero mean and variance σ^2.

Prior to symbol detection, the contribution of the different receive antennas are combined by means of a beamforming vector, $\mathbf{w}$, as follows:

$$\mathbf{y} = \mathbf{w}^T\mathbf{r} \tag{2}$$

In such a case, the received signal-to-noise ratio (SNR) can be maximized by performing a Maximum Ratio Combining (MRC)[5]. To do so, the beamforming vector is computed as the conjugate of the channel response, i.e., $\mathbf{w} = \mathbf{h}^*$. Then, the received signal can be re-written as:

$$\mathbf{y} = \mathbf{h}^H\mathbf{r} = ||\mathbf{h}||^2 s + \mathbf{h}^H\mathbf{n} \tag{3}$$

and one can easily prove that the instantaneous SNR can be written as:

$$\mathsf{SNR} = \frac{||\mathbf{h}||^2 P}{\sigma^2} \tag{4}$$

As the number of receive antennas is increased, so it is the received SNR. However, the involved complexity and cost may make the MRC approach prohibitive for practical implementation. For that reason, we adopt a low-complexity mechanism based on the Hybrid Selection/MRC mechanism already proposed in wireless networks[4]. The following section is devoted to describe this strategy.

III. Hybrid Selection/MRC

In a MRC reception scheme, better performance can be obtained by increasing the number of receive antennas. In doing so, however, the number of complete RF chains must also be increased and so it is the complexity and cost of the system. This negative effect can be drastically reduced by introducing an antenna selection mechanism. Instead of using all the receive antennas, only the best sub-set of them are selected for reception. In Fig. 2, we show a reception scheme based on this reception procedure known as Hybrid Selection/MRC. The system is equipped with N receive antennas, whereas a lower number of RF chains has been considered ($L < N$). In accordance with the selection criterion, the best sub-set of L receive antennas is selected. Once the sub-set of active antennas is selected, their contributions are combined by means of a MRC procedure.

As commented above, considerably savings in terms of complexity and cost of the system can be obtained with the Hybrid Selection/MRC strategy. This is because antenna elements and digital signal processing are considerably cheaper than introducing complete RF chains. As for system performance, it was shown that degradation observed in a wireless environment is slight in comparison with the saving in terms of hardware cost[4]. Basically, the same diversity gain of that obtained with the full antenna system can be achieved but, however, some array gain is lost. In order to shed some light on these concepts, let us introduce the nature of the gains exploited by the MRC scheme. As commented in the previous section, MRC is designed to maximize the received SNR of the link. In order to achieve this SNR maximization, two gains associated with spatial diversity can be exploited:[6]

- *Array gain*: This gain is related to the capability of the multiple antenna system to maximize the received SNR of the link by adapting (matching) the receive beamformer to the channel direction.
- *Diversity gain*: In a multiple-atenna environment, the probability of losing the signal decreases exponentially as a function of the number of uncorrelated antennas. Such an effect is known as diversity gain and it is measured by the diversity order, i.e., the number of uncorrelated paths (antennas) or the slope as the SER decays at high SNR on a log-log scale.

When an antenna selection mechanism is introduced, the best sub-set of antennas is selected. Then, the best paths are chosen for reception. By doing so, the diversity order is the same as it only depends on the total number of uncorrelated antennas used in the selection procedure[4]. However, the array gain results from coherently combining the contribution of the different antennas and, then, it depends on the number of active antennas. As a result, by decreasing the number of active antennas, a fraction of the array gain is lost. In this paper, we are devoted to quantify this lost in a railway scenario, where the importance of diversity gain is emphasized due to the apparition of blockages caused by power supply arches and tunnels.

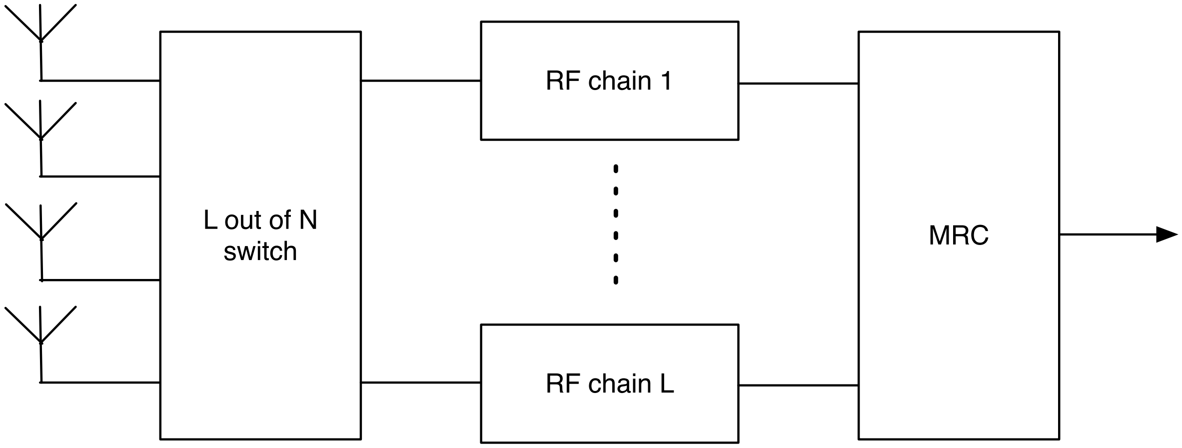


Figure 2. Block diagram of the Hybrid Selection/MRC scheme.

IV. Reception Schemes

As commented above, we propose a Hybrid Selection/MRC strategy to improve the link reliability while keeping a reduced hardware complexity. More precisely, two group of two antennas are placed at beginning and at the end of the train, respectively. From this four antennas, only two antennas are activated and their contributions are combined by means of a MRC strategy.

For the sake of comparison, we also analyze alternative schemes with different degrees of spatial diversity. In particular, the following cases are taken into account in our analysis:

- *Single Antenna (SA):*

This constitutes the first baseline case where the receiver uses only one antenna at all the times. In this situation, $L = N = 1$ (recall that L and N stands for the number of *active* and *available* antennas, respectively). Consequently, the received SNR becomes

$$\mathsf{SNR}_{SA} = \frac{|h|^2 P}{\sigma^2} \tag{5}$$

where h in this case is a scalar representing the channel gain between the satellite and the receive antenna at the high-speed train.

- *Single Antenna with Antenna Selection (SA-AS):*

In this scheme, the *best* antenna ($L = 1$) out of the $N = 4$ antennas available in the train will be selected for data reception, more precisely, the one that maximizes the received SNR

$$\mathsf{SNR}_{SA-AS} = \frac{P}{\sigma^2} \max_{1 \le i \le N} \left\{ |h_i|^2 \right\} \tag{6}$$

where h_i stands for the i-th component of the channel vector $\mathbf{h}$, i.e., the chanel gain associated with the i-th receive antenna.

- *Maximum Ratio Combining (MRC):*

Where the optimum MRC scheme is adopted at the receiver (L=N=4). In this case, the received SNR turns out to be

$$\mathsf{SNR}_{MRC} = \frac{||\mathbf{h}||^2 P}{\sigma^2} \tag{7}$$

In this paper, we also consider MRC reception with only two receive antennas (L=N=2). In order to differentiate this scheme with the four antennas case, the two proposed MRC strategies will be referred as MRC-2 and MRC-4 in the sequel.

- *Hybrid Selection/MRC (MRC-AS)*:

Now, the antenna subset with $L = 2$ out of the $N = 4$ antennas available in the train that maximizes the received SNR will be chosen.

$$\mathsf{SNR}_{MRC-AS} = \frac{P}{\sigma^2} \max_{1 \le i, j \ne i \le N} \left\{ |h_i|^2 + |h_j|^2 \right\} \tag{8}$$

In this case, the maximization is obtained by selecting the two receive antennas with the highest gains.

Finally, in order to further reduce the complexity of the Hybrid Selection/MRC approach, we also propose a simplification of the MRC-AS algorithm, referred as MRC-ASb:

- *MRC-ASb*:

The selection is restricted to only two antenna sub-sets (sub-set of antennas {1,2} and {3,4}) as represented in Fig. 3. That is, the antennas activated for reception are either the two antennas at the beginning of the train or the two antennas at the end. Then, the received SNR can be written as:

$$\mathsf{SNR}_{MRC-ASb} = \frac{P}{\sigma^2} \max \left\{ \left(|h_1|^2 + |h_2|^2 \right), \left(|h_3|^2 + |h_4|^2 \right) \right\} \tag{9}$$

The idea behind this algorithm is that these are the antenna sub-sets considered by the previous MRC-AS approach when the train enters or exits a tunnel. This is due to the fact that, in the other antenna sub-sets combinations, there are always at least one antenna blocked by the tunnel. As shown in the next section, most of the gains obtained with the full MRC-AS can still be extracted with the proposed simplification.

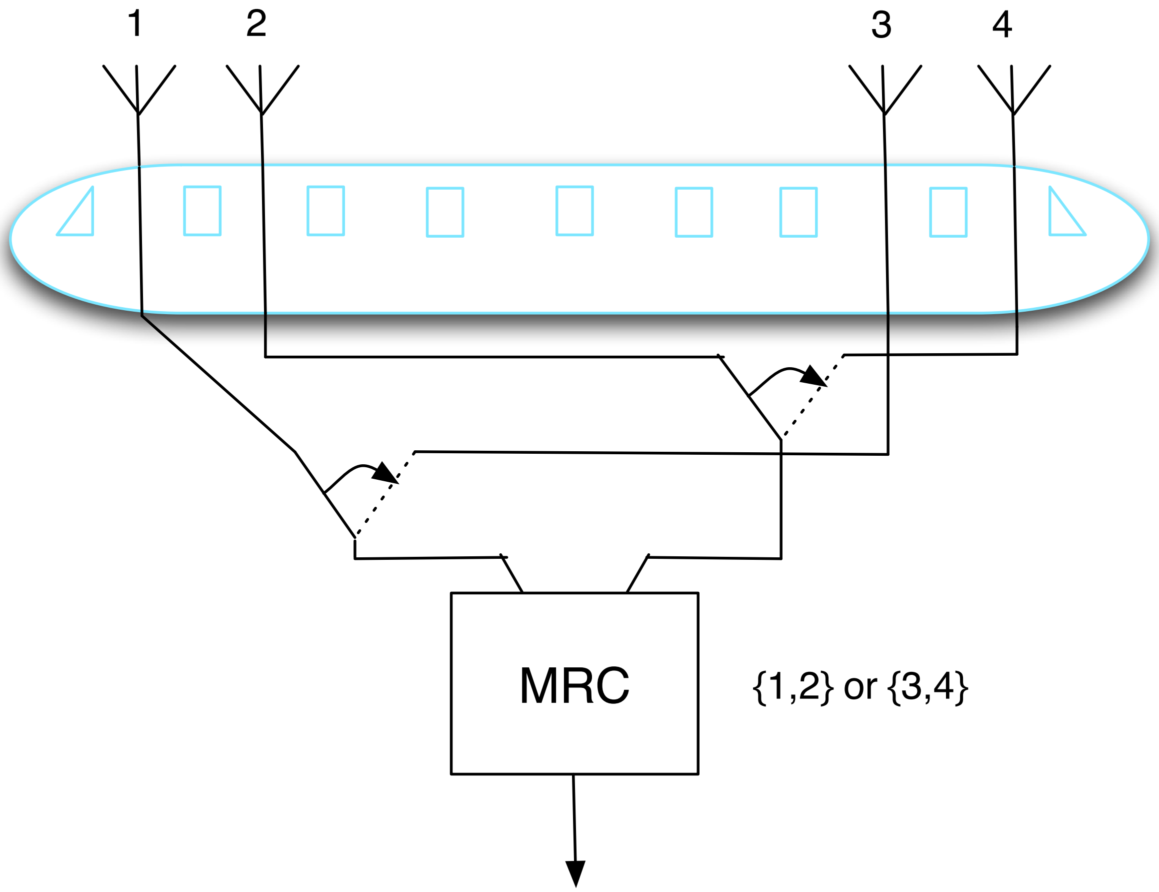


Figure 3. Simplified Hybrid Selection/MRC scheme (MRC-ASb).

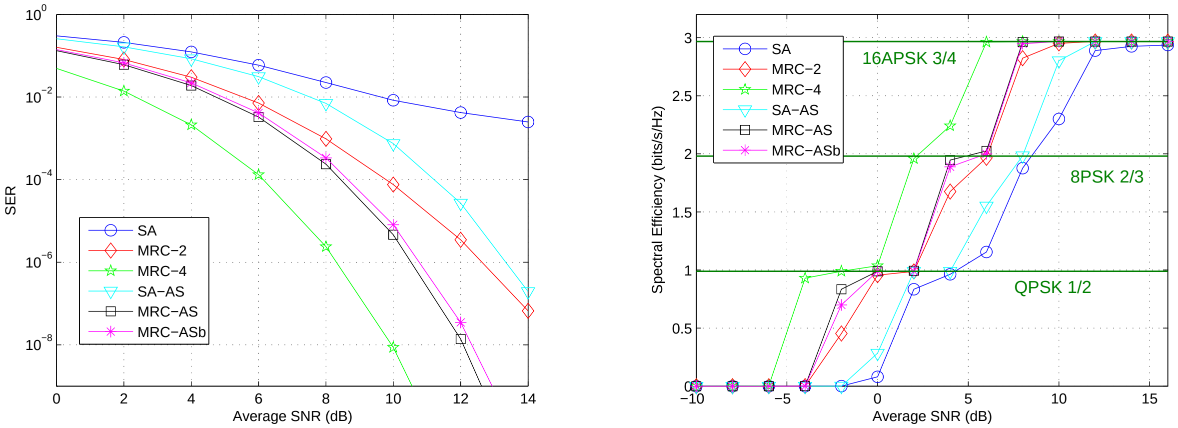
V. Simulation Results

As far as computer simulations are concerned, we consider a scenario where 200 meters high-speed trains are receiving data from a satellite at a speed equal to $v_{train} = 160$ km/h. Power supply arches are separated 30 meters, with fade widths and deep equal to 1 m and 15 dB, respectively. Concerning receive antennas, we take the beginning of the train as the position reference and we place the four antennas at positions 5, 20, 180 and 195 meters. With this antenna deployment, it can be easily shown that more than one antenna cannot be simultaneously blocked by the power supply arches.

We start our analysis by comparing the raw (uncoded) SER of a QPSK transmission associated with the different reception schemes in a LOS scenario as a function of the average SNR, P/σ^2 (see Fig. 4.a). As expected, the worst performance is obtained when the SA strategy is adopted. By introducing multi-antenna schemes, the system is more robust to the railway channel adversities, being MRC-4 the optimum reception

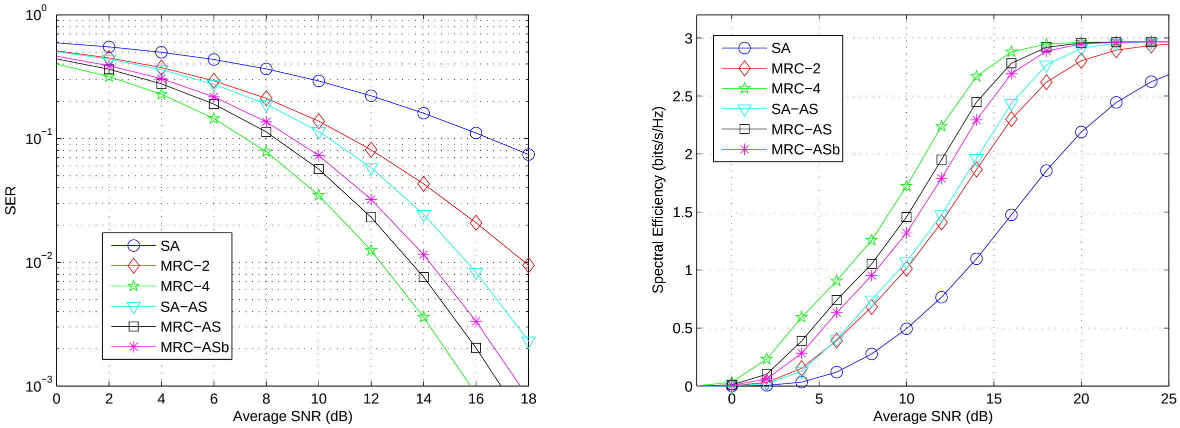
Table 2. ACM modes of DVB-S2 considered in this work.

Mode	Spectral Efficiency (bits/s/Hz)	SNR threshold (dB)
QPSK 1/2	0.988858	1.00
8PSK 2/3	1.980636	6.62
16APSK 3/4	2.966728	10.21



(a) SER vs. average SNR in LOS conditions.

(b) Spectral Efficiency vs. average SNR in LOS conditions.



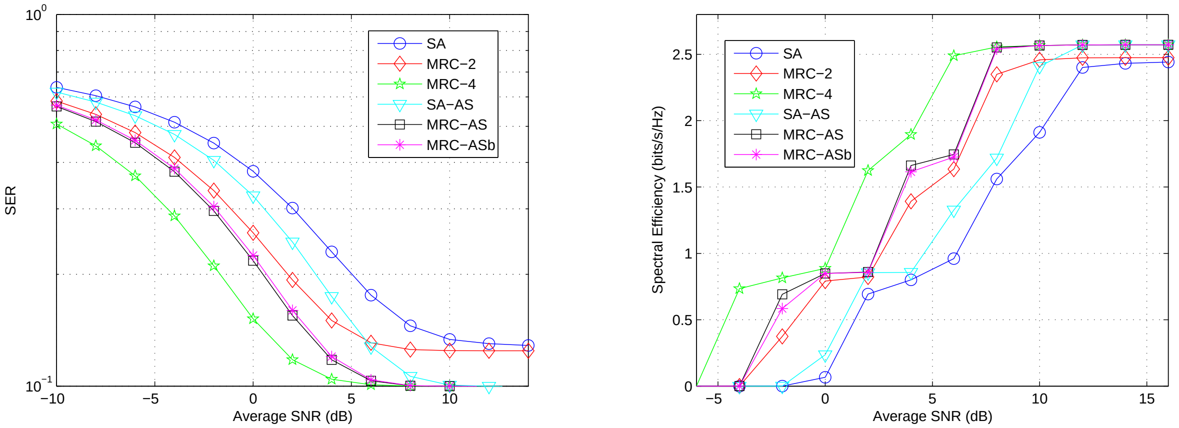
(c) SER vs. average SNR in NLOS conditions.

(d) Spectral Efficiency vs. average SNR in NLOS conditions.

Figure 4. System Performance in terms of SER and Spectral Efficiency for LOS and NLOS scenarios.

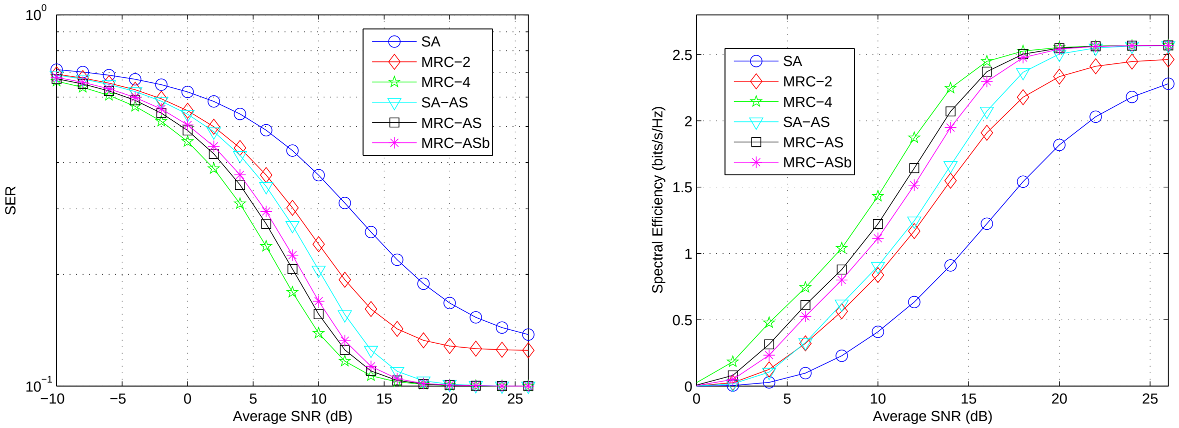
strategy. It is also observed that performance levels obtained with MRC-AS are low- and upper-bounded by MRC-2 and MRC-4, respectively. More specifically, these levels are closer to the MRC-2 case. This is due to the fact that link robustness comes principally from the array gain of the system. By disregarding the power supply arches effect, the channels of the different receivers are quite correlated in this scenario. Therefore, the combination of the contributions of L antennas results in a SNR gain of approximately $10\log_{10}(L)$ dB. This effect is clearly emphasized when curves corresponding to MRC-4 and MRC-AS are compared. In that case, the same number of available antennas is used and so it is the diversity order (i.e, the slope of the curves). Nonetheless, the number of active antennas is the double in the MRC-4 case and, as a result, there exists a shift (in terms of average SNR) of approximately 3 dB. The diversity order is then mainly used to combat the power arches supply effect. This is reflected in the larger slope observed in the MRC-4, MRC-AS, MRC-ASb and SA-AS curves, being for SA-AS not sufficiently large to overcome the array gain obtained with MRC-2. Concerning the MRC-AS and the MRC-ASb approaches, both schemes have the same capability for compensating the power supply arches obstructions. In terms of system performance, this means that most of the MRC-AS gains can be achieved with its simplified version.

In Fig. 4.b, we show results of the proposed schemes in terms of spectral efficiency. Basically, we are taking into consideration the ACM functionality of DVB-S2, where modulation and coding schemes are adapted at the transmit side according to the instantaneous received SNR. Among all the ACM modes of the DVB-S2 standard[1], we consider that only a sub-set of them is available at the transmitter (see Table 2). Performance behaviour is similar to that observed in the SER results but, in this case, curves of the



(a) SER vs. average SNR in LOS conditions.

(b) Spectral Efficiency vs. average SNR in LOS conditions.



(c) SER vs. average SNR in NLOS conditions.

(d) Spectral Efficiency vs. average SNR in NLOS conditions.

Figure 5. System Performance in terms of SER and Spectral Efficiency for LOS and NLOS scenarios with tunnels during the journey.

MRC-AS, MRC-ASb and MRC-2 are quite closer. In the proposed system, the high differences between the SNR thresholds (as shown in Table 2) makes that considerably gains in terms of instantaneous SNR are needed to select an upper ACM mode. In a LOS scenario, the fluctuations of the instantaneous SNR with respect to the average SNR are quite reduced. Therefore, the introduction of selection diversity does not give extra gains when spectral efficiency is measured. For the same reason, it is observed that the transition between the different ACM modes are well defined. Notice the steps observed in the spectral efficiency curves associated with the values of the available ACM modes.

When the different schemes are analyzed in a NLOS scenario, one can appreciate how performance of all the schemes is deteriorated as the channel is more aggressive (see Figs. 4.c and 4.d). Apart from that, it is clearly observed how the introduction of antenna selection mechanisms are better exploited in a scenario where the gains of the different antennas are more uncorrelated. For instance, SA-AS performs better than MRC-2 in this case. Concerning the MRC-AS and MRC-ASb approaches, their curves are slightly less overlapped (MRC-AS has more antenna sub-sets to exploit diversity) and their results are closer to MRC-4. In terms of SER, curves associated with the MRC-AS and MRC-ASb are only at 0.4 and 0.65 dB of MRC-4, respectively, whereas gains of 4 and 3.75 dB are obtained when compared with MRC-2. Concerning spectral efficiency, curves are smoother than the LOS case as the received SNR has higher fluctuations. That is, for a given average SNR, the probability of selecting different ACM modes is higher. Therefore, the difference in terms of system performance when different reception schemes are adopted is clearly defined. As for the MRC-As and MRC-ASb approaches, gains of 2dB can be obtained with respect to the MRC-2 strategy.

Finally, we show in Fig. 5 results corresponding to a scenario where tunnels appear during the journey. To obtain that results, we have considered data collected from Italian high-speed railway paths (see work by Sciascia *et al.* for further details[7]). As shown in the plots of Fig. 5, the relative position of the SER and spectral efficiency curves obtained with the different reception schemes have a similar behavior than that observed in the case without tunnels. The main difference, however, is that there exists an error floor in SER curves, which is translated to a saturation effect on spectral efficiency performance. By focusing on SER results, one can observe that the level of the error floor is lower in the cases where antenna selection mechanisms are introduced (SA-AS, MRC-AS, MRC-ASb) or four antennas are activated (MRC-4). In these situations, the probability of having all the antennas inside the tunnel is lower. Besides, the loss of MRC-AS and MRC-ASb approaches with respect to MRC-4 is considerably lower when tunnels are considered (in both the LOS and NLOS scenarios). This is emphasized in the NLOS case, where the shift between curves is equal to only 1dB. Basically, performance is considerably limited by the tunnel fading and one must bear in mind that the number of effective antennas is the same in MRC-4, MRC-AS and MRC-ASb cases when the train enters or exits a tunnel. Finally, it is worth noting that performance strongly depends on the railroad paths. In this work, we have considered a situation where tunnels are considerably higher than the train length[7] and, as a result, the use of gap fillers can be reduced but is still required. In a situation where the tunnels had a high probability of having a length of the order of the train length, one would observe minimal performance losses in MRC-4, MRC-AS and MRC-ASb. In order to verify that situation, different scenarios corresponding to European railway networks will be studied in future research.

VI. Conclusions

In this paper, we have proposed a Hybrid Selection/MRC approach to alleviate the impairments introduced by the railway channel. The proposed strategy have been compared with other multi-antenna techniques. It has been shown that, for a fixed number of RF chains, better performance can be obtained with the Hybrid Selection/MRC approach with respect to the classical MRC approach. More specifically, the gain obtained with the proposed technique is emphasized in NLOS scenarios, where 4 dB and 2 dB shifts in average SNR can be achieved when the SER and the spectral efficiency are analyzed, respectively. In order to further reduce receive complexity, a simplified version of the Hybrid Selection/MRC approach has been derived showing that losses in system performance are negligible (approximately 0.25 dB). Finally, the different schemes have been analyzed in a scenario where tunnels appear during the journey. In that case, both the SER and the spectral efficiency performance are limited by error floors and saturation effects. However, it has been proved that these negative effects have a lower impact when the proposed antenna selection based schemes are adopted.

Future work in the field will encompass the study of the proposed scheme in different railway networks of Europe. The use of more realistic simulation techniques will also be addressed.

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