Analysis of A&F Mobile Relay Nodes with Power Control and Link Selection in HSR Scenarios

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***Abstract*—In this paper, a theoretical study of the use of Amplify&Forward (A&F) Relay Nodes (RNs) with Power-Control-and-Link-Selection (PCLS), in a High-Speed-Railway (HSR) scenario is presented. The MRNs have been standardized by the 3GPP and is one of the proposed solutions to improve the Quality of Service (QoS) and the user's throughput on vehicles in high mobility scenarios. Nevertheless, many items have not been investigated in depth until now, like transmission power control in the MRNs and link selection by on-board users. Under this hypothesis, firstly a Power-Control-and-Link-Selection (PCLS) algorithm is developed. In addition, the advantages of using Multiple-Input and Multiple-Output (MIMO) schemes, Resource Allocation (RA) together with Beamforming techniques have been analyzed. Numerical simulations indicate that the combination of PCLS with MIMO capacities and RA-Beamforming schemes in the MRNs substantially improves the throughput of on-board users and reduces the transmission power of MRNs.**

***Index Terms*—Mobile Relay Nodes, High Speed Railway, Power Control, Link Selection, MIMO-Beamforming, Throughput**

I. Introduction

Relay Nodes (RNs) are a "retransmission technology" introduced by LTE (Long Term Evolution), which are commonly preferred due to increased transmission rate, expanding coverage, and reliability. The idea behind this technology is to make use of relay nodes to extend network coverage and improve throughput of the system [1]. Nowadays, with the increment of smartphones and tablets accessing the internet inside of mobility scenarios, both the researchers and academia communities are investigating an economic solution to be of usage with the intense data traffic of vehicular users. In [2], 3^{rd} Generation Partnership Project (3GPP) considered the development of Mobile Relay Nodes (MRNs), with identical functionalities that Fixed Relay Nodes, but, the main difference is that it provides communication to users within the vehicle (trains or buses) during their journey [3], [4]. In this paper, we exploit the concept of Amplify&Forward Mobile Relay Node, in which the received signal is amplified and forwarded to the destination, usually the User Equipment (UE). This solution is quite simple and does not introduce delays.

Recently, most transmission and reception schemes and algorithms have been proposed to be applied to MRNs. One interesting scheme is Multi-Input and Multi-Output (MIMO), which provides a large spectral efficiency gain without increasing power and bandwidth. Besides, employing MIMO techniques will help mitigate some of the main problems in these environments like path loss and high vehicular penetration [5]. To guarantee the Quality of Service (QoS) of on-board users in these scenarios is a challenge. Nevertheless, in these environments the capacity is non-uniformly distributed and a low density of macro users exists, therefore, there are resources in the eNB that are not completely exploited. In this sense, another technique utilized to improve the capacity is beamforming scheme, in which the main lobe of the antenna pointed in a particular direction, in this case, towards the MRNs [6].

Generally, the main issue in the planning of the cell is that in the nearest zone to the eNB, the channel conditions are better than farthest area, obtaining high capacity. In the dedicated networks to carry out service to HSR environments, it exists circumstances that the train across near to eNB, and in these cases, the channel conditions of the on-board users and of the MRNs placed in the train are exponentially improved. In this context, the optimal strategy is that on-board users will be connected to the eNB and is not necessary employing additional power by the MRNs, which can be optimized during the travel of the train. In previous works [7], [8], the power control has been presented in a fixed environment and [1] studied mobile scenario. However, power control and link selection in mobile environments with MRNs have not been studied in depth yet.

In this paper, the main contribution is the development of the Power Control and Link Selection (PCLS) algorithm in an HSR environment with A&F MRN. Besides, the advantages that involve PCLS implementation in transmission power in the MRN are investigated. From these conditions, the authors will be focusing on improving the on-board user's capacity, when MIMO technique, Beamforming scheme and Resource Allocation capabilities are implemented.

II. Mobile Relay Nodes in HSR

HSR environment offers a major challenge to guarantee the desired QoS levels. In the scenario without MRN, the on-board users present great disadvantages respect to macro users, where the eNB would attend them as normal users [9]. In this instance, the on-board users suffer high penetration losses, rapid temporal variations in the radio channel, etc.

MRNs are generally placed at the top of vehicles and their antennas have a high Line-of-Sight (LOS) to the eNB antenna, which will enhance the receiver performance. The MRN scenario is generally composed of three links. The MRN presents two radio links: one between its outdoor antenna and eNB (backhaul link), which is characterized by $\mathbf{H}_{eNB-R}$ channel, and another between its indoor antenna and the on-board users (Access Link), which is described by $\mathbf{H}_{R-S}$ channel as is presented in Fig. 1. Overall MRNs provide sure services, with the assumption that the relay link has a much better channel than regular UEs. On the other hand, the on-board users are attached by another radio link (Direct Link), which is established between eNB and on-board user and is depicted by $\mathbf{H}_{eNB-S}$ as shown Fig. 1.

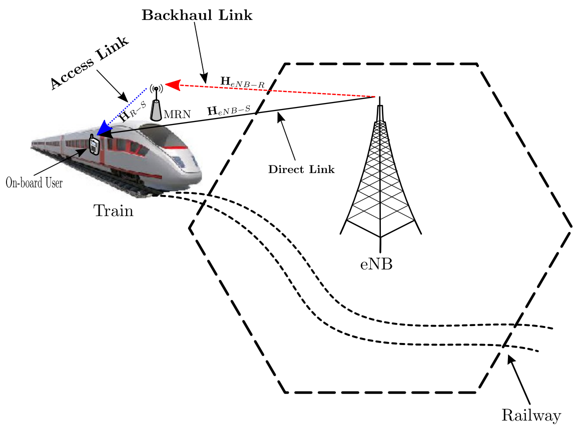

Fig. 1. MRN scenario scheme. Different types of links.

In this paper an A&F MRN installed on the roof of a railway carriage is considered. The Relay Node operates in half-duplex mode, so Backhaul Link and Access Link operate on the same frequency band, i.e., by Time Division Duplex (TDD), so return link and Access link of the MRN are never active at the same time [10].

A. Power-Control-and-Link-Selection Algorithm

In this subsection the developed algorithm for implementing the PCLS is explained. The purpose of this algorithm is to perform a transmission power control of the MRN during travel and switch the service link of the on-board users depending on the received Signal-to-Interference-plus-Noise-Ratios (SINR). If it is considered that the transmission power is known, to estimate the SINR, it is necessary to study the characteristics of the propagation channel, incorporating path loss and shadowing. The WINNER II [11] channel model is used, which will be described in the next subsection. Therefore, the calculation of the SINR for on-board users, depending on whether their connection is through the direct link (D_L) or the access link (A_L), can be performed by:

$$\gamma_{UE,i}^{D/A} = \frac{P_{Tx} + G_{Tx} + G_{Rx} - L_p - \beta}{\sum_{j=1}^{N} P_{I,j} + N_{UE,i}}, \tag{1}$$

where P_{Tx} is the transmitter power, G_{Tx} describes the transmitter gain and G_{Rx} represents the gain of the on-board user. The above parameters will be chosen according to whether the connection is by the direct link $\gamma_{UE,i}^{D_L}$ (P_{Tx} and G_{Tx} of eNB) or if the connection is through the access link $\gamma_{UE,i}^{A_L}$ (P_{Tx} and G_{Tx} of MRN). Besides, L_p and β are the path loss and shadowing values, respectively. $P_{I,j}$ is the overall interference from macro cell signal, $j = 1, ..., N$ the eNB number interfering eNB and $N_{UE,i}$ is the Gaussian noise coefficient.

The proposed Algorithm 1 is based on the direct and access links shown in Fig. 1. To control the transmission power from MRN and select the link of the on-board users according to the best SINR are the main aims of the PCLS algorithm. Firstly, SINR of the access and backhaul links of the on-board users are estimated through (1) and the link that presents the best SINR to each on-board user is selected. Then, by means of **Search**$_L()$ function they are found the connected on-board users through $\mathbf{H}_{eNB-S}$ channel. Finally, taking into account the connected user number inside the train to the eNB (N_{act}), the transmitter power of the MRN is calculated, instead of the criterion of other authors [1].

Algorithm 1: Power Control and Link Selection (PCLS)

Input : P_M, N_u^t
Output: P_{txM}, L_s
for $i \longleftarrow 1 : N_u^t$ **do**
  Estimate $\gamma_{UE,i}^{D_L}$ and $\gamma_{UE,i}^{A_L}$
  if $\gamma_{UE,i}^{D_L} \geq \gamma_{UE,i}^{A_L}$ **then**
    $L_s(1,i) = D_L$;
  else
    $L_s(1,i) = A_L$;
  end
end
N_{act} = **Search**$_L(L_s(1,:))$;
if $N_{act} < \frac{N_u^t}{2}$ **then**
  $P_{txM} = P_M - \frac{0.5 * N_u^t}{100} * N_{act}$;
else if $N_{act} == \frac{N_u^t}{2}$ **then**
  $P_{txM} = \frac{P_M}{2}$;
else if $N_{act} > \frac{N_u^t}{2}$ & $N_{act} > N_u^t$ **then**
  $P_{txM} = \frac{P_M}{2} - \frac{0.5 * N_u^t}{100} * (N_{act} - \frac{N_u^t}{2})$;
else if $N_{act} == 0$ **then**
  $P_{txM} = 0$;
else
  $P_{txM} = P_M$;
end

In Algorithm 1, P_M is the transmission power maximum of the MRN, N_u^t describe the total of on-board users. P_{txM} and L_s are the transmission power of the MRN after applying the PCLS and selected links to offer service to the on-board users according to their SINR, respectively.

B. Channel Modelling and MIMO Capacity

To model the propagation channel for the link between the eNB and the MRN, the WINNER II model is used in a D2a scenario. It is assumed that the train is moving through a rural scenario where LOS exists. Nevertheless, the on-board users will go to suffer variation in their channel model, given that do not remain always attached to MRN. Therefore, two types of propagation channels are considered, A1 and D2a model according to the WINNER II. On the other hand, for macro users, WINNER II channel model D1 scenario will be used as it models a rural macro cell environment with enough precision [11].

A modified Shannon capacity formula proposed in [12] is used and is given by:

$$C = B * \Psi * \Lambda * \log_2(1 + SINR/\Pi), \tag{2}$$

where B denotes the bandwidth, Ψ adjusts the system bandwidth efficiency, Λ is a correction factor, and Π adjusts the SINR implementation efficiency of LTE. In this formula, the setting values depend on the used transmission schemes. SISO and 2×2 MIMO were implemented in the developed simulator and the corresponding parameters are represented in Table I [12]. In MIMO technique, we consider the Alamouti code, which was shown to be the optimum block code for two transmit antennas and time-domain coding [13].

TABLE I
SHANNON FIT PARAMETERS

Tx/Rx schemes	$\Psi * \Lambda$	Π
SISO	0.56	2
2×2 MIMO	0.62	1.4

C. Scheduling and Beamforming Algorithms

This subsection explains the Scheduling and Beamforming algorithms employed to offer the resource allocations of the LTE system. Firstly, scheduling is discussed, in which the LTE standard defines some mechanisms to enable packet scheduling [1]. Round Robin (RR) algorithm is based in a cyclic allocation of the radio channel for all users in the system. Besides, it is a fair strategy, through which each user will use the $\mathbf{H}_{eNB-S}$ channel during the same time period without considering propagation conditions. RR algorithm is assumed when the scenario without MRN is considered and the on-board users are connected directly to the eNB.

Dedicated Resource Allocation (DRA) Algorithm is used in order to allocate the resources between the on-board and macro users, as is shown in the simplified diagram in Fig. 2. Taking into account the output of the Algorithm 1, DRA has been developed. Firstly, $\mathrm{N}^t_{D_L}$ and $\mathrm{N}^t_{A_L}$ are calculated, which represent the total number of the connected on-board users to $\mathbf{H}_{eNB-S}$ and $\mathbf{H}_{R-S}$ channels, respectively. Considering previous parameters, $\mathrm{C}^t_{D_L}$ and $\mathrm{C}^t_{A_L}$ are determined, both define the total capacity (Mbps) required by $\mathrm{N}^t_{D_L}$ and $\mathrm{N}^t_{A_L}$, respectively. After that, the **det**() function determines the number of Resource Blocks of the LTE system from B (system bandwidth) and is stored in RBs. It should be noted that in the implemented algorithm, the criteria followed prioritize the traffic of on-board users, assigning the rest of the resources, if any, to macro users. On the other hand, $\mathrm{RB}^t_{D_L}$, $\mathrm{RB}^t_{A_L}$, and $\mathrm{RB}^m \in \mathbb{Z}_{>0}$ correspond to the algorithm outputs, which hold the allocated resources to $\mathrm{N}^t_{D_L}$, $\mathrm{N}^t_{A_L}$, and macro users, respectively.

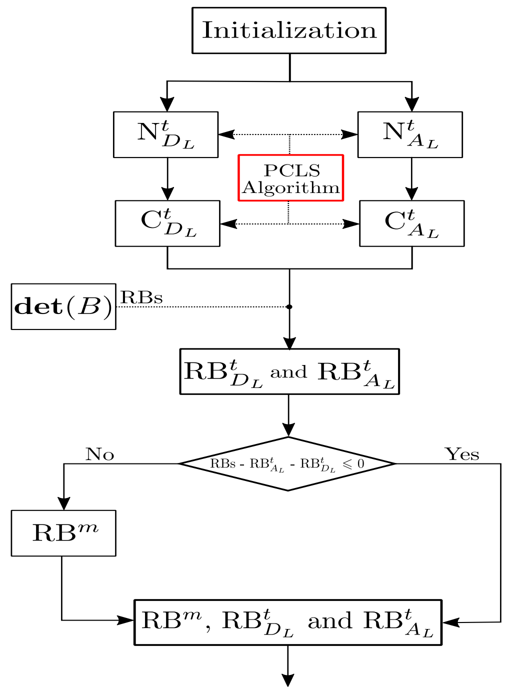

Fig. 2. Flowchart of the DRA algorithm.

An adaptive beamforming scheme capable of ideal tracking and control of beam direction has been implemented in Algorithm 2. Its practical realization supposes a technological challenge, which is not the subject of this article, but is the scheme proposed by the 3GPP in [14]. It has been assumed that beamforming is established between the eNB and the MRN, as shown in Fig. 3.

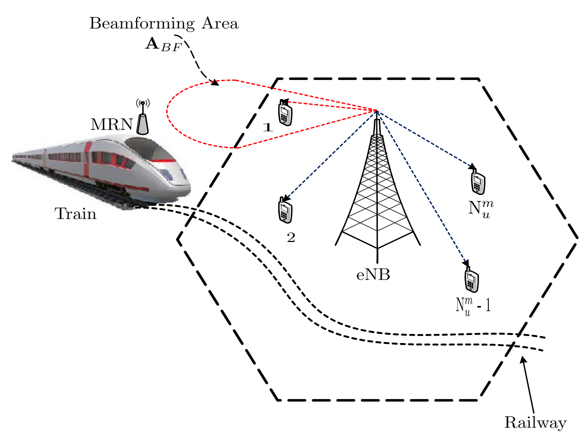

Fig. 3. MRN scenario scheme with Beamforming technique.

Algorithm 2 describes the resource allocations demanded by N^t_u users inside the train, which will be distributed in $\mathrm{RB}^t_{D_L}$ and $\mathrm{RB}^t_{A_L}$, like was presented previously. Nevertheless, the rest of the resources, if any, are assigned to macro users, where the criteria followed prioritize the traffic of macro users inside Beamforming Area ($\mathbf{A}_{BF}$). However, the allocated resource blocks to the rest macro users are decreased 50%, and the other half is assigned to on-board users.

Algorithm 2: DRA-Beamforming with PCLS

Input : N_u^t, N_u^m, B, Q^t, Q^m
Output: RB^m, RB_{BF}^m, $\mathrm{RB}_{D_L}^t$, $\mathrm{RB}_{A_L}^t$
Calculate Algorithm 1;
RBs = **det**(B);
$\mathrm{C}_{D_L}^t = \mathrm{C}_{A_L}^t = \mathrm{C}_{BF}^m = 0$;
for $i \leftarrow 1 : N_u^t$ **do**
  if $L_s^i == A_L$ **then**
    $\mathrm{C}_{A_L}^t = \mathrm{C}_{A_L}^t + Q_i^t$;
  else
    $\mathrm{C}_{D_L}^t = \mathrm{C}_{D_L}^t + Q_i^t$;
  end
end
$\mathrm{RB}_{D_L}^t = \frac{C_{D_L}^t}{eff * B^{RB}}$, $\mathrm{RB}_{A_L}^t = \frac{C_{A_L}^t}{eff * B^{RB}}$;
if *(RBs - $RB_{D_L}^t$ - $RB_{A_L}^t$) $<= 0$* **then**
  $\mathrm{RB}^m = 0$, $\mathrm{RB}_{BF}^m = 0$;
else
  $\mathrm{N}_{BF}^m = \mathbf{A}_{BF}(N_u^m)$;
  if *N_{BF}^m == 0* **then**
    $\mathrm{RB}^m = \frac{RB^m}{2}$, $\mathrm{RB}_{D_L}^t = \mathrm{RB}_{D_L}^t + \frac{RB^m}{2}$;
    $\mathrm{RB}_{A_L}^t = \mathrm{RB}_{A_L}^t + \frac{RB^m}{2}$, $\mathrm{RB}_{BF}^m = 0$;
  else
    for $j \leftarrow 1 : N_{BF}^m$ **do**
      $\mathrm{C}_{BF}^m = \mathrm{C}_{BF}^m + Q_j^m$;
    end
    $\mathrm{RB}_{BF}^m = \frac{C_{BF}^m}{eff * B^{RB}}$;
    if *(RB^m - RB_{BF}^m)$<= 0$* **then**
      $\mathrm{RB}_{BF}^m = \mathrm{RB}^m$, $\mathrm{RB}^m = 0$;
    else
      $\mathrm{RB}^m = \frac{RB^m - RB_{BF}^m}{2}$;
      $\mathrm{RB}_{D_L}^t = \mathrm{RB}_{D_L}^t + \frac{RB^m}{2}$;
      $\mathrm{RB}_{A_L}^t = \mathrm{RB}_{A_L}^t + \frac{RB^m}{2}$;
    end
  end
end

In the developed DRA-Beamforming with the PCLS algorithm, the main parameter is Q^t ($\in \mathbb{R}_{>0}^{1 \times N_u^t}$), which is a vector that contains the QoS of each on-board user. As shown in Algorithm 2, firstly Algorithm 1 is calculated. Then, $\mathrm{C}_{D_L}^t$ and $\mathrm{C}_{A_L}^t$ are calculated taking into account Q^t. After that, $\mathrm{RB}_{D_L}^t$ and $\mathrm{RB}_{A_L}^t$ are obtained, therefore, if it exists resource blocks, are allocated RB_{BF}^m and $\mathrm{RB}^m \in \mathbb{Z}_{>0}$, which correspond to the total resource blocks assigned to macro users inside or outside the Beamforming Area, respectively. In Algorithm 2, N_u^m, N_{BF}^m and Q^m ($\in \mathbb{R}_{>0}^{1 \times N_u^m}$) are, respectively, the total number of macro users for each cell, the total number of macro users inside $\mathbf{A}_{BF}$ and the QoS of the macro users. On the other hand, C_{BF}^m, eff and B^{RB} are the total capacity (Mbps) required by the N_{BF}^m macro users, the efficiency ($\in \mathbb{R}_{>0}$) of the LTE system for 64-QAM, and the bandwidth of the resource block (kbps).

III. Results and Discussion

A. Layout, Railway Scenario and Parameters

The simulated LTE network scenario is comprised of eight cells (from Cell 1 to Cell 8), where cell 1 is attended by eNB_1, cell 2 is served by eNB_2 and so, respectively, until eNB_8 as shown in Fig. 4. It has been established that the scenario is in a rural zone, multipath is not expected to be a dominant factor. Generally, it will exist a LOS between the external antenna of the MRN and the eNBs. The train moves from left to right side in the scenario presented at a speed of 350 Km/h, and travels 8 Km. As observed in Fig. 4, the railway tracks find situated during all travel between 290 and 350 meters of each eNB. Besides, the distance between eNBs is 2 Km and each cell provides service to $\mathrm{N}_u^m = 20$ macro users, which have been placed randomly in the scenario. We have considered macro users with a velocity of 3 Km/h. On the other hand, inside the train, we have performed a distributed randomly, and spatially uniform to the $\mathrm{N}_u^t = 50$ on-board users. In Table II the main parameters used in the simulation have been summarized. Besides, our implementation scenario and performance evaluations are carried out using the Matlab Software.

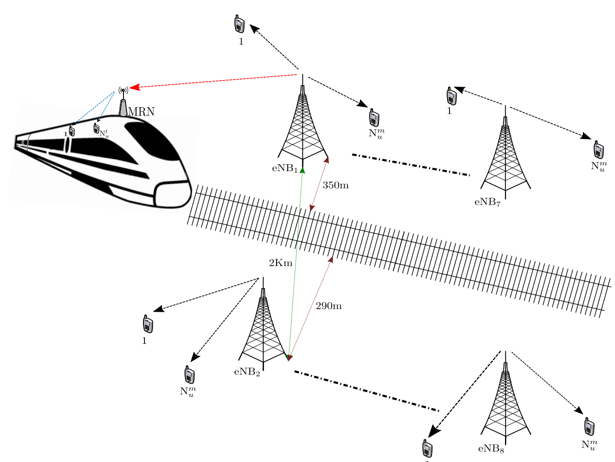

Fig. 4. Mobile Relay Node and eNBs in the HSR scenario.

B. Impact of PCLS on MRN and On-board Users

This simulation evaluates the impact of the PCLS on link selection by the on-board users and transmission power of the MRN during the path followed by the train. At the beginning of the simulation, all on-board users are connected to the MRN through A_L. Nevertheless, during all the path, the PCLS algorithm analyses both D_L and A_L, and it decides to switch the link of the on-board users following what was explained in Algorithm 1. In this circumstance, the resource allocations of the on-board users connected to the D_L are served from the eNB.

TABLE II
MAIN SIMULATION PARAMETERS

Bandwidth (B)	10 MHz
Carrier frequency	1800 MHz
Tx/Rx schemes	SISO and 2×2 MIMO
Modulation	64-QAM
eff	4
Cell Radius	1 Km
Simulation time	80 s
eNB transmit power	46 dBm
eNB-Gain	18 dB
MRN transmit power max.	20 dBm
Noise-MRN	7 dB
MRN-Gain	10 dB
UE-Gain	2 dB
Noise-UE	9 dB
Traffic-Types(kbps)	VoIP(64), Video(600), Web(120)

In Fig. 5, the connected on-board user number to $\mathbf{H}_{eNB-S}$ channel during all the travel is shown. Besides, a red graphic with the total number of on-board users is presented to compare. It can be appreciated in Fig. 5 that eight peaks exist, which represent the eNBs in the scenario. It can also be noted that in four of the base stations, which are closer to the train track, all on-board users are connected to them. When the train wagon is between eNBs all on-board users are connected to the MRN.

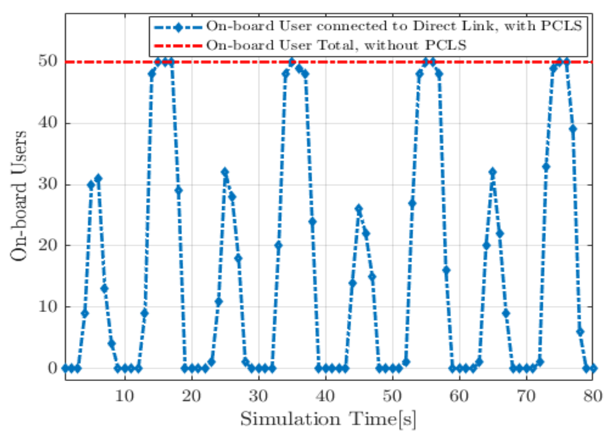

Fig. 5. Variation of the number of on-board users connected by Direct Link to eNBs.

The transmission power variation by the MRN as a function of on-board users connected during all the path of the train when the PCLS algorithm is used or not is presented in Fig. 6. Firstly, when the PCLS algorithm is considered, the power values vary from the transmission power maximum (20 dBm = 100 mW) by the MRN to the minimum power (0 dBm = 1 mW), when there are not on-board users connected. It can be seen that there exists a close relationship between the number of on-board users connected to the eNB and the transmit power of the MRN. On the other hand, when the PCLS is ignored the transmission power is constant (20 dBm = 100 mW). Considering the PCLS algorithm, it was possible to save an average of 22.72 mW of power, which represents 22.72% of the transmission power maximum (100 mW) of the MRN.

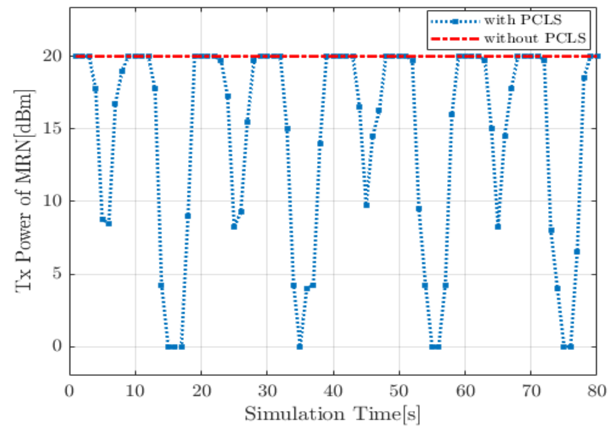

Fig. 6. Variation of the transmitted power by the MRN, with and without PCLS algorithm.

C. Impact of PCLS on On-board User performances

Fig. 7 shows the obtained results for the Cumulative Distribution Function (CDF) versus the throughput [Mbps] of different situations in the analyzed HSR scenario. For example, the performance of on-board users is compared to the situation where MRN is not deployed on the roof of the train carriage and the PCLS algorithm is not considered.

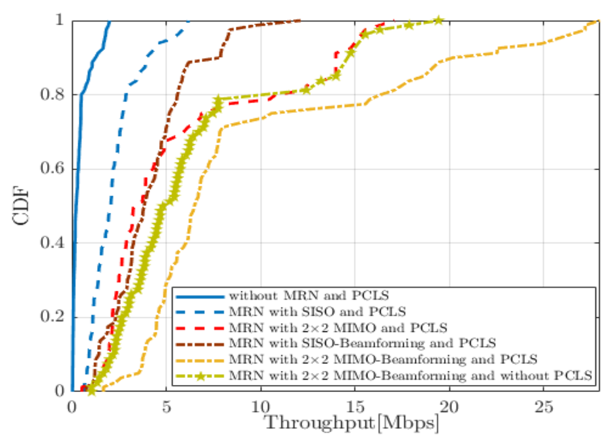

Fig. 7. On-board users' throughput for different scenarios.

These results show that on-board users' performance with the MRN and the PCLS greatly outperforms the obtained results when on-board users are connected directly to the eNB. For example, the difference in the throughput of on-board users with or without MRN and PCLS is 2.7 Mbps for 90% of the time. In addition, other scenarios with MRN and PCLS have been studied: 2×2 MIMO, SISO plus DRA-Beamforming and 2×2 MIMO and DRA-Beamforming. In these scenarios, the throughput is incremented gradually. The obtained throughput with SISO and DRA-Beamforming is 7.89 Mbps, 2×2 MIMO is 14 Mbps, and 20.22 Mbps employing 2×2 MIMO and DRA-Beamforming. Another curve is considered for comparison, in this sense 2×2 MIMO and DRA-Beamforming are exploited in the environment with MRN but ignoring the PCLS algorithm, under this focus, the on-board users obtain 14.77 Mbps, which decreases 5.45 Mbps when is used the PCLS algorithm.

Other simulation results are presented in Fig. 8. The idea behind such simulation is to study the performance of macro users with or without MRN and PCLS in the simulator. In Fig. 8 can be seen that the macro user's capacity without MRN and PCLS degrades 500 kbps when compared with the scenario where MRN and PCLS are inserted, which in the latter is clearly visible that the resource allocation is performed fairly with DRA Algorithm given the increase of the macro users performance. Nevertheless, when 2×2 MIMO, SISO plus DRA-Beamforming, and 2×2 MIMO plus DRA-Beamforming are implemented the performance of macro users is deteriorated considerably. As can be seen in the aforementioned figure, the degradation of throughput in macro users is greater as the Mobile Relay Node implements Beamforming techniques. It should be emphasized that "Flat Zone" in Fig. 8 is produced when the train is in transit through the scenario and on-board users are connected directly to eNB, and due to the beamforming scheme implementation, given that in this circumstance alone they are assigned 50% of the RBs to macro users outside $\mathbf{A}_{BF}$ and the rest is to on-board users.

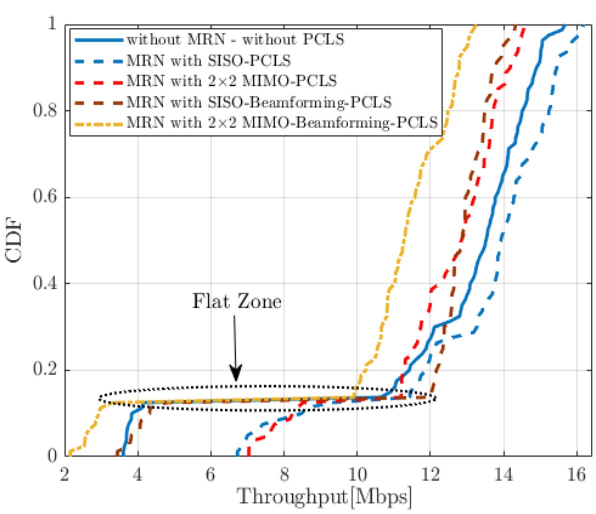

Fig. 8. Macro users' throughput for different scenarios.

IV. Conclusions

In this paper, a theoretical study of the use of Amplify&Forward (A&F) Relay Nodes (RNs) with Power-Control-and-Link-Selection (PCLS), in a High-Speed-Railway scenario is presented. Under this focus, the authors studied the efficiency of implementing a link selection on the on-board users and power control in the A&F MRN in the HSR environment. Besides, different scenario schemes have been analyzed: SISO, MIMO, SISO and DRA-Beamforming, MIMO and DRA-Beamforming capacity using MRNs and PCLS. The results show that on-board users get better throughput when deploying a MIMO and DRA-Beamforming scheme, together with the PCLS algorithm. Moreover, transmission power variation by the MRN is decreased considerably with the PCLS algorithm. Naturally, the performance of macro users is degraded with the use of Mobile Relay Nodes and when transmission techniques (MIMO), Beamforming and PCLS algorithm are implemented.

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