A MAC/PHY Simulation Platform for Multi-Packet Reception in 802.11 Networks

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Abstract—This paper presents an hybrid discrete-time simulation platform, based on the integration between network simulator-2 (ns-2) and MATLAB, which implements a PHYsical (PHY) and Medium Access Control (MAC) layer design for enabling Multi-Packet Reception (MPR) in an 802.11 network using advanced antenna systems. In the proposed MPR scheme, which introduces minimal MAC layer modifications, a node asynchronously accesses to the medium as long as the number of ongoing communications lies within a given threshold. Heterogeneous scenarios are considered by taking into account distinct load thresholds for nodes equipped with different antenna systems. The simulated MAC/PHY design maintains backward compatibility with legacy 802.11 stations and is numerically tested in Wireless Mesh Networks (WMNs) in presence of multipath-fading and multihop communications.

Index Terms—Smart antenna modeling; discrete-time simulation; IEEE 802.11; MATLAB; ns-2; multihop.

I. INTRODUCTION

One of the most popular discrete-event tools for the simulation of telecommunication networks is ns-2 [1]. ns-2 is an open source project written in the C++ programming language at the Berkeley National Laboratory and improved by various research groups [2]. Similarly to other discrete-event simulators, ns-2 offers advantages in terms of scalability and simulation time, since the state of the system changes only when a new event occurs [3]. Conversely, the physical layer characteristics, such as modulation, antenna system, and coding scheme, as well as the behavior of the wireless channel can be implemented in detail using a discrete-time approach. The main drawback of a discrete-time tool is the very long simulation time usually required to obtain the results. Hence, an hybrid discrete-event discrete-time approach may represent an effective tradeoff between model accuracy and simulation duration. A detailed PHY layer model can be properly implemented using the proprietary software MATLAB. The MATLAB software offers a high level programming approach able to implement procedures and functions that simulate the PHY layer behavior. The novel hybrid approach addresses a considerable limit of ns-2, namely its simplified propagation channel modeling [4]. This limitation becomes particularly significant when advanced antenna techniques, such as smart antenna systems, must be included in the simulations. A smart antenna system is constituted by an antenna array, whose radiation pattern can be dynamically controlled to perform the electrical beam steering to a desired direction, and null steering to reject interfering signals [5]. In a scenario where the network nodes are able to adapt their radiation patterns, the actual antenna gain becomes a crucial quantity for evaluating the performance of the network. Recently, some MATLAB extensions have been proposed to include smart antenna systems in OPNET and OMNeT++ discrete-event simulators [6,7]. Instead, to the best of authors’ knowledge, the unique ns-2 tool for the simulation of multiple antenna arrays and multipath has been proposed in [8]. This paper extends the tool proposed in [8] by implementing a novel MAC/PHY design for enabling asynchronous MPR in heterogeneous 802.11 networks using multiple antennas. The novel simulation platform exploits the information provided by the antenna system to manage the decrease of the backoff counter and guarantees the coexistence of the nodes using different antenna systems. The modifications applied to the 802.11 MAC layer are minimal and the presented multiple antenna system implementation allows one to simulate heterogeneous networks, including the case of 802.11 legacy stations. The novel simulation platform is capable of evaluating the performance of complex scenarios introducing accurate PHY and propagation models in ns-2. Angular multipath’s effects are accurately taken into account and the simulator also introduces fading impairments in the propagation model. Furthermore, the effects of channel coding are investigated by considering the adoption of turbo codes and convolutional codes.

The paper is organized as follows. Section II presents the main theoretical concepts of the modified PHY design. Section III describes the proposed simulation platform. Section IV shows the novel MAC scheme. Results are provided in Section V. Finally, conclusions and discussions of further enhancements of the simulator are given in Section VI.

II. MODELING METHODOLOGY

A. Smart antenna system

The adopted smart antenna model accounts for the physical antenna system, constituted by an array of $N$ elements, and for the signal processing unit, which calculates the complex array excitations $w_1, ..., w_N$ that are applied to the array elements by the beamforming unit in order to generate the power gain...
The possibility to account for the single element pattern $g_n(\phi)$ in (1) allows one not only to consider non-omnidirectional radiators, but also to account in detail for mutual coupling between the array elements, which may lead to considerable distortions of the final pattern $G(\phi)$.

### B. Multipath

Multipath effects in the angular domain are modeled by using the concept of equivalent radiation pattern [9]:

$$F(\phi) = \int_0^{2\pi} G(\phi') p(\phi' - \phi) d\phi',$$

(2)

where $p(\phi)$ is the Power Azimuth Spectrum (PAS) normalized to the transmission power, which represents the probability density function (pdf) of the DoAs corresponding to an active node. $F(\phi)$ takes into account that a signal replica incoming from an undesired Line Of Sight (LOS) direction $\phi' \neq \phi$ are received with higher gains, leading to an increase of the received interference. Similarly, the signal incoming from the desired source in the LOS direction is received with the maximum gain, but the replicas are received with lower gains, leading to a decrease of the desired signal power. The pdfs currently implemented in the proposed MATLAB extension are the truncated Laplacian [10], the truncated Gaussian [11], and the pdf corresponding to a ring of scatterers surrounding the transmitting node [12]. The scenario corresponding to absence of multipath can be obtained by choosing $p(\phi)$ as the Dirac function.

### III. Simulation Platform

The architecture of the extension is reported in Fig. 1, which shows the interactions between MATLAB software and the modified ns-2 source code. Fig. 1 also shows the interfaces required to enable the exchange of data between the two tools. A novel multihop extension is introduced by employing multiple preferred nodes, as further detailed in this section.

#### A. MATLAB extension

The MATLAB extension is a set functions and procedures implementing the channel-antenna model described in Section II that can be executed stand alone in MATLAB. The MATLAB language has been chosen because it provides a simple and immediate development environment for implementing signal processing algorithms and functions adopted for the simulation of the PHY layer. In fact, the functions can be developed by writing few lines of code, since a large number of mathematical procedures are already present in the MATLAB environments. In this way also non C++ experts can improve the quality of the physical layer simulation of ns-2.

The main component of the MATLAB extension is the function SAS.m, which provides the equivalent radiation pattern $F(\phi)$ in (2). This function accepts a large list of parameters allowing the simulations of multiple antennas features. The generation of equivalent radiation pattern requires to specify
as input an array containing the DoAs, an array containing the distances, an array containing the transmitting powers, the type of the array geometry and the number of radiation elements. Furthermore, in order to account for angular multipath one has to specify the statistical distribution of multipath and the angular spread. Finally, an additional parameter may be specified in order to account for the mutual coupling between array elements consideration.

B. Ns-2 modifications

The modifications applied to the ns-2 simulation platform are described without detailing the ns-2 architecture, assuming a basic understanding of the ns-2 software by the reader. The 2.33 version of ns-2 is considered [1].

The introduction in ns-2 of the developed channel-antenna extension requires the implementation of a new class, called SmartAntenna. Besides, the existing method WirelessPhy::SendUp must be modified in order to evaluate the Signal to Interference Ratio (SIR) at the receiving node using the new antenna model. This evaluation is performed by the new implemented method GainCalc, which provides the receiving pattern according to the position of the nodes. Fig. 1 depicts the flow chart of the receiving procedure at the receiving node. Note that the receiving node invokes MATLAB in order to calculate the equivalent receiving radiation pattern $F(\varphi)$ only if it has not been already evaluated in a previous communication, with an identical scenario of active sources. In absence of mobility this considerably reduces the overall simulation time, since useless repetitions of identical link simulations are avoided. An additional modification of the method MAC802_11::recv_timer is required in order to enable the complete knowledge of the SIR variations of each packet due to other concurrent transmissions. The monitoring of the SIR is performed by storing the time instants marking the beginning and the conclusion of the last $T$ transmissions of each node in a global table Last_txs, where the $T$ value is selected in order to cover the duration the DATA packet. As a matter of fact, the method MAC802_11::recv_timer, which defines the MAC behavior at the end of a packet reception, evaluates the SIR for the entire packet duration, accounting for the possible presence of fading, modeled by a Rayleigh distributed envelop constant over the transmission of the packet. The MAC802_11::recv_timer also considers the effect of the error correcting codes. In particular, the simulator defines two possible criteria to account for the code: the t-criterion, in which a packet is correctly received if its SIR is larger than a given threshold $\text{SIR}_t$ for the entire reception time, and the s-criterion, which considers the sequence of SIR values and, according to the modulation, provides a sequence of rates, estimated using the sphere packing bound, whose average value (sustainable rate) is compared to the selected code rate [13]. This second approach is more realistic, mainly for turbo codes, while, for convolutional codes, an offset of 5 dB is added to the SIR used to estimate the sustainable rate.

C. Integration of ns-2 with MATLAB

Since the MATLAB package contains also a C++ Compiler, the developed MATLAB set of functions can be converted in C++ language. This solution avoids the use of the extension as a stand alone application, guaranteeing a reduction of the simulation time, with respect to an approach in which two distinct processes have to exchange data. The conversion of the developed MATLAB package to C++ language generates four files: libSAS.so, representing the dynamic library and describing the user-defined function; libSAS.cff, representing a Component Technology File (CTF) archive that includes the MATLAB based content (.m files); libSAS.cpp and libSAS.h that must be included in the source code of ns-2. Moreover, the above-mentioned MATLAB libraries should be copied to ns-2 directories for allowing a successful compilation of the modified software. Finally, a set of functions has been implemented in order to convert the standard C++ arrays used by ns-2 in the non-standard C++ mwArrays used by MATLAB and vice versa. This conversion is a key point to allow the exchange of information between ns-2 and MATLAB, considering that the two tools operate on different data types.

D. Multiple preferred nodes

In the simulation platform each node may send packets only to a station belonging to the “preferred nodes” set. In [8] each node considers only one preferred node. This paper introduces multiple preferred nodes enabling the simulation of extended WMNs, where each node may be connected to several other neighbours and packets may be sent through different routes. The set of preferred nodes is listed by the ns-2 tcl script during the node creation process. Every time a node receives a packet it checks if the transmitter belongs to its preferred nodes set. Upon a successful match, the receiving station uses the radiation pattern provided by the smart antenna system, otherwise an omnidirectional antenna is employed. The routes among nodes are specified at physical layer, however a routing protocol is also required. It has to be noted that the routing protocol is constrained by rules specified by preferred nodes. However, the study of the performance of the routing protocol is beyond the scope of the paper and is left to further investigations.

IV. HETEROGENEOUS ASYNCHRONOUS MPR MAC

As shown in [9] for an homogeneous scenario, where all nodes are equipped with an identical antenna system, the channel behavior, the number of antennas, the array processing technique, and the network topology determine the maximum number of simultaneous communications $L$ that can be sustained by the network. Consider an heterogeneous 802.11 network consisting of $n$ contending nodes in which the generic node $i$ is equipped with an antenna system of $N_i(\geq 1)$ antenna elements. If $N_i = 1$, just a single omnidirectional radiator is available and the node $i$ behaves as a typical 802.11 station. Instead, if $N_i > 1$, the node $i$ can be equipped with a processing unit in order to produce a power gain pattern $G_i(\varphi)$, where $\varphi$ is the azimuth angle. This implies that the node $i$ is able to suppress interferences created by other nodes. Hence, node $i$ is characterized by a threshold $L_i$, which accounts for its ability. Thus, during the omnidirectional PHY Carrier Sensing (CS) of the medium, an estimation $l_i$ of the
number of active transmitters may be observed. When the basic access mechanism is adopted, these \( l_i \) transmitters may include sources transmitting the DATA packet and/or destinations transmitting the ACKnowledgement (ACK) packet, since the scenario is asynchronous. Two quantities must be considered to enable a contending source \( i \) to properly exploit this information at MAC layer. The first quantity takes into account that the estimation \( l_i \) may be lower than the real value \( l \) of the transmitters that are active, since the degrees of freedom of a multiple antenna system with \( N_i \geq 2 \) elements enable the estimation of up to \( N_i - 1 \) sources. Besides, an 802.11 legacy node can just sense the presence of energy and so is completely unable to derive the number of active nodes. Hence, the maximum number of distinct transmitters that can be estimated by the generic \( i \)-th node is:

\[
l_i^{\text{max}} = \max\{1, N_i - 1\}, \tag{3}
\]

and, from the point of view of the \( i \)-th node, all scenarios in which \( l \geq l_i^{\text{max}} \) are equivalent to \( l = l_i^{\text{max}} \).

Defining now the set \( \mathcal{R}_i \), containing the \( l_i \) currently receiving nodes and the desired destination of the node \( i \), one can evaluate the current access threshold for the node \( i \) as:

\[
L_{\text{cur}}^i = \min_{k \in \mathcal{R}_i} L_{\text{th}, k}, \tag{4}
\]

which, together with (3), enables the formulation of a proper criterion for managing the access to the medium. More precisely, the transmission of the contending source \( i \) may be performed if both following conditions are satisfied:

\[
l_i < l_i^{\text{max}}, \tag{5a}
\]

\[
l_i \leq L_{\text{cur}}^i, \tag{5b}
\]

where the condition (5a) guarantees that the number of sources is reliably estimated, while the condition (5b) guarantees that the transmission of the source \( i \) can be sustained by the other currently receiving nodes and by the desired destination. In particular, the condition (5b) allows the coexistence of \( L_{\text{cur}}^i + 1 \) transmissions, instead of \( L_{\text{cur}}^i \). However, this possibility does not imply that the network is operating beyond the single node capabilities, since, as shown in [14], the threshold of each node must be selected to a value strictly lower than the number of sustainable communications, which, as a matter of facts, quantifies the network capacity [9]. Conditions (5a) and (5b) can then be used to manage the decrease of the 802.11 backoff counter. In particular, if (5a) and (5b) are satisfied, the backoff counter of the source \( i \) can be decreased, otherwise the backoff counter is frozen and reactivated once (5a) and (5b) are satisfied again for a Distributed InterFrame Space (DIFS). When the counter reaches the zero value, the contending node attempts to transmit selecting an omnidirectional operating mode [15]. This choice increases the probability that other potential sources sense the transmission, including the 802.11 legacy ones, thus reducing the deafness phenomenon that may lead to useless attempts of transmission towards already busy nodes.

A noticeable advantage of the proposed design is the lack of MAC layer modifications with respect to the 802.11 standard, since the increase of complexity, including the antenna system, and the check of conditions (5a) and (5b) involve only the PHY layer. The adopted approach is substantially based on a generalization of the Clear Channel Assessment (CCA) function of the 802.11 standard obtained using (5a) and (5b). In fact, if a node \( i \) has a unique antenna, \( l_i^{\text{max}} = 1 \) and the source can access to the medium only if no transmissions are sensed, since just two states are possible: \( l_i = 0 \) (“idle”) and \( l_i = 1 \) (“busy”), as in the original 802.11 CCA function.

V. RESULTS

The developed MATLAB-ns-2 platform is used to simulate the proposed MAC/PHY solution for MPR in asynchronous heterogeneous 802.11 networks. The parameters used in simulations are shown in Table I, where the data rate of 12 Mbits/s is obtained using a Quadrature Phase Shift Keying (QPSK) modulation along with a channel code characterized by a coding rate equal to \( R_C = \frac{1}{2} \) [16]. The packet generation process is assumed to be Poisson distributed with mean \( \mu \).

Sixty seconds of network activity are monitored for each simulation. Different scenarios are simulated in order to provide an exhaustive summary of the capabilities of the simulation platform.

The first set of simulations involves a regular topology of \( n = 38 \) nodes placed on two concentric rings, where the sources lie in the outer ring and the destinations in the inner one at a distance of 25 m (Fig. 2a). Fig. 3 shows the throughput for different channel coding techniques and reception criteria considering this scenario. The throughput obtained when the nodes are IEEE 802.11g compliant, which is the lower, is taken as reference for the comparison with further results. It has to be noted, that the correct reception policy for IEEE 802.11g compliant nodes refers on the omnidirectional receiver power. Due to the closeness of the nodes the throughput corresponds at most to a single communication. Conversely, the correct reception policy implemented into smart antenna systems

### Table I: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>SIFS</td>
<td>10 µs</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 µs</td>
</tr>
<tr>
<td>Slot time</td>
<td>20 µs</td>
</tr>
<tr>
<td>Data rate</td>
<td>12 Mbits/s</td>
</tr>
<tr>
<td>Packet size</td>
<td>1470 bytes</td>
</tr>
<tr>
<td>CW</td>
<td>80 meters</td>
</tr>
</tbody>
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![Fig. 2. Simulated topologies: a) regular topology with \( n = 38 \) nodes, b) random topology with \( n = 10 \) nodes.](image-url)
relies on the calculation of the SIR during the reception. It can be seen that the adoption of a threshold on the SIR to establish the success/failure of a packet reception may lead to pessimistic results when the ACK packets are taken into account. This is because the destination suppresses only the directions sensed as active at the beginning of the reception. However, since the DATA packets have a longer duration, often the ACK packets are received from not suppressed directions providing a high interference power. Hence, the SIR may fall under the SIR threshold for a short time and the t-criterion may pessimistically establish the failure of the reception, as exemplified in Fig. 4. Conversely, if the complete SIR behavior is considered (s-criterion), more realistic results are obtained. The use of channel coding is able to cope to the fall of the SIR for a short time, maintaining a proper communication quality. Fig. 3 also confirms that the adoption of a turbo code guarantees a more efficient compensation of the interference created by all the concurrent (DATA and ACK) transmissions with respect to a convolutional code. The SIR threshold, which is considered during the simulations, derives from the adopted PHY characteristics. The bit rate of 12 Mbits/s with correspondent modulation QPSK, the channel coding with a coding rate equal to $R_C = \frac{1}{2}$ and a Packet Error Rate (PER) set to 1% lead to $\text{SIR}_t = 5\text{dB}$. The $\text{SIR}_t$ may take different values depending on the adopted communication characteristics.

The second set of simulations is performed considering a random topology comprehending $n = 10$ nodes, whose locations are shown in Fig. 2b, alongside with their thresholds $L_t$. The propagation channel is affected by block fading, where the fading envelope is assumed to be Rayleigh distributed, and it is also characterized by a Laplacian distributed multipath phenomenon with 10 degrees of angular spread. The s-criterion is used for packet reception. Fig. 5 shows that turbo codes provide a higher throughput with respect to the one offered by convolutional codes. Moreover, noting that a single-link with a data rate of 12 Mbits/s, where a channel code with a coding rate equal to $R_C = \frac{1}{2}$ is used, offers a throughput of approximately 5 Mbits/s, one can observe from the aggregated throughput shown in Fig. 5 that the proposed MACPHY design enables the simultaneous activity of almost four links. The last set of simulation introduces multihop transmissions by enabling multiple preferred node for each station. A slight modification of the random scenario is considered, where nodes are divided into groups in order to form multihop routes. More explicitly, nodes 7, 10, 9, 5, 8, 6, form two singlehop links, respectively, while nodes 1, 2, 4, 3 are grouped to create a dual hop link. Moreover, nodes 1, 5 and 7 behave as sources, while nodes 3, 6 and 9 act as destinations. Finally, nodes 2, 4, 8 and 10 are enabled to forward packets from the source to the destination and vice versa. Fig. 6 shows the aggregated throughput for the three links considering the s-criterion for packet reception and employing turbo and convolutional codes in a block fading affected environment. The nodes thresholds $L_t$ are the same as depicted in Fig. 2b. Even though the performance of the four scenarios considered in Fig. 6, the turbo codes provide a higher throughput with respect to the convolutional codes. Furthermore, it has to be noted that the aggregated throughput is limited due to the higher number of hops in the considered scenario, which reduces the achievable end-to-end throughput for the sake of increasing the network reliability.

VI. CONCLUSIONS AND FUTURE WORK

A novel discrete-time discrete-event simulator for the simulation of smart antenna systems in 802.11 networks has been
The presented tool can be further extended to examine a larger set of scenarios. In particular, further studies may extend the simulator in order to consider high rank scenarios, in which spatial diversity and Multiple Input Multiple Output (MIMO) solutions may be implemented in the MATLAB software. Furthermore, the proposed platform may be adapted in order to include cooperative communication, which may also exploit the benefits offered by smart antenna systems in order to further increase the performance of hybrid MPR networks. Besides, since the novel simulator introduces static routes in a scenario employing smart antennas systems by specifying preferred nodes, this approach may restrict the degrees of freedom of the routing protocol. Further studies should take into account the interaction between the smart antennas defined routes and the routing protocol. In particular, a cross-layer designed solution may be used to improve the overall performance of the network. Thus, the novel simulator may be modified to account for realistic WMN routers. These devices are characterized by up to four different network interfaces, which may be introduced in the hybrid simulation platform in order to accurately model a realistic scenario. All the above issues are the objective of ongoing studies. A downloadable version of the presented simulator tool will be available at [17].

REFERENCES