Simulation of 802.11 Radio-over-Fiber Networks using ns-3

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ABSTRACT

The radio-over-fiber (RoF) technology is a suitable solution to provide high bitrates and to improve the IEEE 802.11 WLAN coverage. Those systems use an optical network to distribute the radio signal from the access point to several remote antennas. Our research project consist in the investigation of the Medium Control Access (MAC) layer performance of those networks. We decided to achieve our work with ns-3 since it provides an accurate Wi-Fi model. However, there is a lack of model for RoF simulations in ns-3. As a result, we developed a new physical layer in ns-3 based on the existing Yans Wi-Fi modules to enable the simulation of such hybrid networks. This paper shows how ns-3 can be used for the simulation of 802.11 RoF systems and compare our simulation results achieved in ns-3 with the results obtained with Opnet by other research groups.

General Terms

Performance, Design, Verification

Keywords

Simulator, ns-3, Radio-over-Fiber (RoF), IEEE 802.11, MAC, performance evaluation

1. INTRODUCTION

The current trend in access networks is to bring the fiber to the users in order to provide higher data throughputs. On the other hand, for the last years, we observed an important growth of wireless systems as users need more and more to be connected everywhere and at anytime. The radio-over-fiber (RoF) technique is a promising solution to merge the flexibility and the mobility offered by wireless networks with the capacity and the transparency of fiber-fed networks [1–3]. Moreover, the utilization of a Distributed Antenna System (DAS) is shown to improve the energy consumption efficiency of wireless networks [4].

In RoF systems, a Central Station (CS) or an Access Point (AP) uses an optical network to transmit radio signals to distributed Remote Antenna Units (RAUs). The RAUs then convert the optical signal to the electrical domain and transmit the signal over the radio channel to the mobile users. The invert operation is performed when a station needs to transmit packets to the AP.

A big range of wireless services can be distributed over a radio-over-fiber structure (Wi-Fi, ZigBee, WiMAX, ...). In our research, we investigate the transmission of IEEE 802.11 (Wi-Fi) signals using radio-over-fiber architectures. Figure 1 illustrates the case of an 802.11 RoF DAS configuration with two distributed antennas.

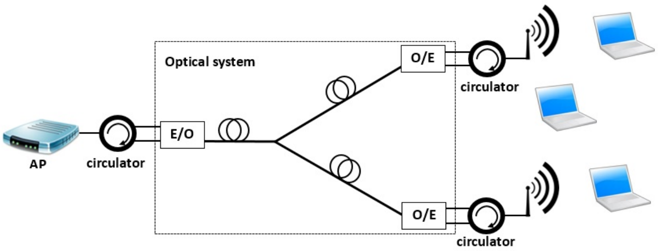

Figure 1: 802.11 system using a RoF DAS architecture.

The transmission of radio signals over optical architectures is a very attractive topic to the research community, and lots of publications about RoF subjects were observed for the last years. There are two main research activities about RoF: one investigates the transmission techniques over optical networks in order to propagate a RF signal with good performance over long distances [1, 2], whereas the second one concerns the analysis of the MAC layer operation of wireless protocols using RoF architectures in order to improve the performance of those systems. This last topic requires the utilisation of a network simulator in order to quantify the performance of RoF networks under given conditions [3].

In the existing ns-3 modules, there is no existing models for the simulation of RoF networks. In order to study the performance of the IEEE 802.11 Medium Access Control (MAC) layer performance in RoF systems, we developed a new physical layer in ns-3 based on the existing Yans Wi-Fi model implemented in the simulator. We integrated an optical channel module in the simulator to model the transport

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of wireless signal over the optical fiber. We also developed a new device model to represent the RAU entities in the simulator in order to set their position in the RoF network. Our proposed 802.11 RoF model is able to investigate the network performance for mono-antenna 802.11 RoF architectures as well as Distributed Antenna Systems (DAS) RoF. Our contribution can be found in the wiki page related to ns-3 optical network models [5].

In this paper, we first explain the advantages and the challenges linked to an 802.11 transmission over a RoF network. Then, we discuss our implementation of 802.11 RoF in ns-3. Afterwards, we validate our model by comparing the simulation results provided by ns-3 with results obtained with Opnet and theoretical evaluations. Finally, we provide an example simulation that considers a RoF DAS scenario.

2. MOTIVATION

Radio-over-fiber technology involves the transmission of RF signals over an optical network. In those systems, the signal coming from the AP is imposed on the optical carrier and transmitted through an optical network. It is then converted back to the electrical domain by means of a photodetector so that the output signal is a copy of the input signal. A RoF system can be advantageously used to distribute several wireless services to the end users using an existing optical access network. Among the wireless signals that can be distributed in RoF infrastructures, our work focus on the transmission of IEEE 802.11 packets.

In comparison to traditional 802.11 wireless access networks, the utilisation of a RoF DAS infrastructure (figure 1) offers a large number of advantages: it enables an optimal network coverage by placing the antennas close to the mobile users, which allows to reduce the emitted power at each remote antenna site [4]. Moreover, there are no handover while mobile users are moving from one cell to another cell since it stays connected to the same access point. Furthermore, RoF configurations enable the centralization of whole the processing functions at a central site, reducing the complexity of the antenna units and facilitating the maintenance of those networks [1, 2].

However, the IEEE 802.11 MAC protocol was not initially developed for RoF systems. Indeed, in traditional Wi-Fi systems, the maximum delay is expected to be less than 1 µs, whereas in RoF networks, the propagation delay is around 5 µs per kilometer of optical fiber. The physical layer dependent parameters as well as the mechanisms defined in the IEEE 802.11 standard may then not be adapted to a RoF transmission. It is therefore important to adapt the current protocol in order to optimize the performances of those systems.

In order to investigate the network performance of 802.11 communications over a RoF link, we implemented a new model in ns-3 for the simulation of those hybrid infrastructures. In the next section, we describe how the existing Wi-Fi model provided by ns-3 has been modified to enable the simulation of 802.11 RoF networks.

3. 802.11 ROF MODEL IN NS-3

The first effect of inserting optical links between the AP and the wireless stations is to increase the propagation time. Indeed, it does not only correspond to a pure air propagation delay, but is mainly linked to the optical propagation delay (time needed to transport the radio signal over the optical fiber).

At the MAC layer, the RoF transmission is seen as an additional delay compared to traditional wireless networks. In order to study the network performance of RoF systems, we first considered a basic optical channel model for which we assumed that the optical transmission is modeled as an extra delay equal to the time needed by the radio signal to travel along the fiber link and a linear loss equal to the attenuation introduced by the optical link (figure 2). Furthermore, in order to obtain a more accurate optical channel, more sophisticated models for the propagation of RF signals over fibers should be added in the simulator.

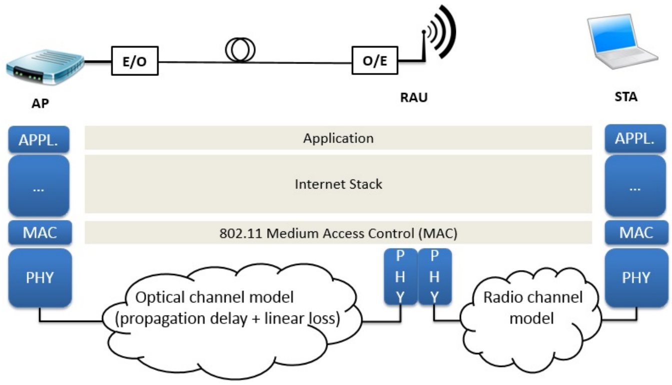

Figure 2: 802.11 RoF model.

The IEEE 802.11 model in ns-3 is relatively complete and is organized as shown on figure 3. This model can still be used for 802.11 RoF simulations, but the channel module needs to be changed. Since RoF transmissions needs optics, an optical channel component needs to be added in ns-3. Besides, a new device model must be implemented to simulate the behavior of remote antenna units.

In our proposed model (figure 4), a *WirelessChannel* module, which is an adapted version of the existing *YansWifiChannel* in order to fit with our implementation, works together with an *OpticalChannel* module which is responsible for computing the delay and the loss due to the transport of the 802.11 signal over the optical network. An *ApWifiPhy* instance is attached to the access point node and *StaWifiPhy* instances are attached to each station node. Those two classes have similar functions than the existing *YansWifiPhy* module but are fitted to the underlying channel. In addition, a new physical layer module *RofRelayWifiPhy* has been defined in the simulator, which is responsible to forward packets coming from the optical channel to the wireless channel and to forward packets coming from the wireless channel to the optical channel. Each RAU node of the network is attached to a *RofRelayWifiPhy* instance.

When the AP transmits a packet, it is sent to all RAUs

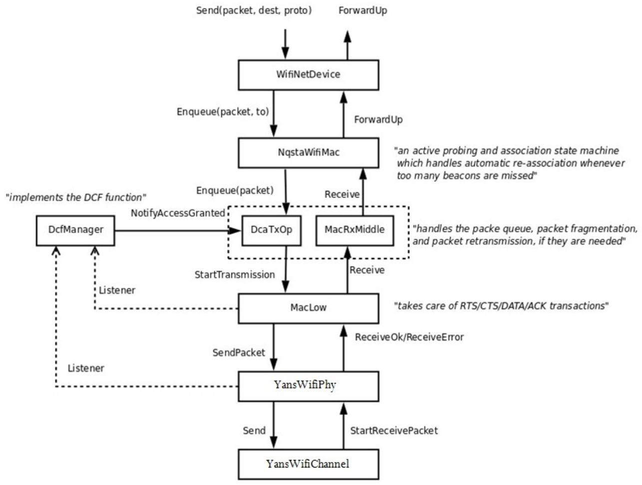

Figure 3: Existing 802.11 model in ns-3.

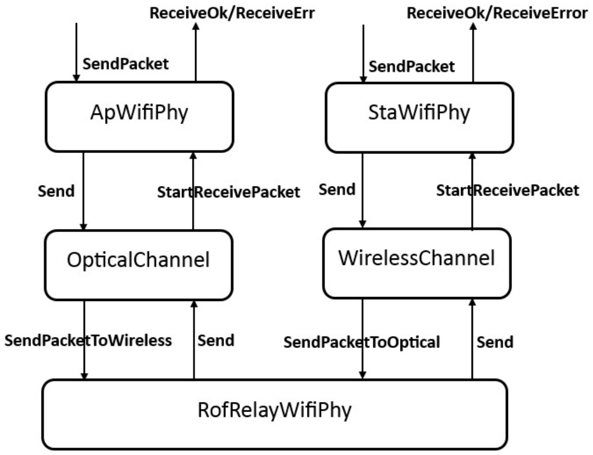

Figure 4: Proposed 802.11 RoF physical layer model implemented in ns-3.

attached to the *OpticalChannel* module, and the optical signal sent by a RAU is only transmitted to the AP and is not received by other RAUs. In the *WirelessChannel* implementation, when a RAU has a packet to send, it is received by all the stations and all the other RAUs. Depending on the received power of the incoming packet, the receiver (StaWifiPhy or ApWifiPhy) decides to synchronize on the signal if it is higher than a fixed threshold. As a result, a station located near a RAU will receive the packets sent by all the other RAUs, but since the received power of those packets will be under the threshold, it will correctly synchronize on the signal coming from its closest RAU. Moreover, when a station is located between several RAUs, it will receive several times the same signal coming from the AP, as observed in real RoF deployments.

In the *OpticalChannel* module, the calculation of the optical propagation time (τ) is equal to the distance (L) between the AP and the RAU divided by the velocity of the signal (v) in the optical fiber, which can be computed thanks to the fiber refractive index (n) and the light speed velocity in the vacuum (c_0):

$$\tau = \frac{L}{v} = \frac{L \cdot n}{c_0} \tag{1}$$

The reflective index of the fiber can be tuned by the user in order to change the velocity of the signal in the optical network. The linear loss is also configurable. By default, those parameters are respectively set to 1.5 and 0.2 dB/km, resulting in a classical delay of 5 µs per kilometer of optical fiber.

The key point of our model, instead of simply adding an additional delay in the existing Yans Wi-Fi model, resides in the ability to set the position of each individual node (access point, remote antenna units and stations) of the network on a grid. To do so, we implemented a RAU device model in the simulator (*RofRelayDevice*) which is responsible to hold together all objects used by a remote antenna. The position of each RAU device is used by the *OpticalChannel* and the *WirelessChannel* modules to calculate the length of the fiber link between the AP and each RAU node and the air distance between each wireless node (remote antenna units and stations). Those values are then used to compute the propagation delay and the propagation loss introduced by each medium.

Our model in ns-3 can thus be used for any radio-over-fiber configuration using the IEEE 802.11 protocol. In the next sections, we report the validation of our model and we provide an example simulation using our RoF DAS implementation in ns-3

4. VALIDATION

Other research groups have investigated the MAC performances of 802.11b RoF networks using Opnet [1, 3]. In this section, we first compare the simulation results achieved with our RoF model using the same parameters with those published by other research groups in order to validate our model implemented in ns-3 (version: ns-3.15). Then, we validate our implementation with a theoretical evaluation for both 802.11b and 802.11g RoF networks. To do so, we considered an ideal wireless channel (no interference, no error, ...). Once validated, our model could be used to investigate the performance of RoF networks when the wireless medium is not ideal.

In [1, 3], authors used Opnet to analyze the impact of the propagation delay introduced by the optical fiber on the 802.11b throughput. The simulation setup considers a point-to-point RoF system with a single station which is continuously transmitting UDP data packets to the AP (figure 5). The parameters set for the 802.11b simulations are depicted in table 1.

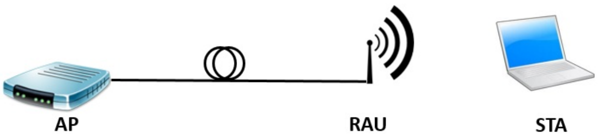

Figure 5: Simulation scenario considered for validation purpose.

Table 1: Simulation parameters

Parameter	IEEE 802.11b	IEEE 802.11g
SIFS	10 µs	10 µs
Slot time	20 µs	9 µs
ACK timeout	450 µs	450 µs
Long retry limit	7	7
Minimum backoff window	31	15
Maximum backoff window	1023	1023
Data rate	11 Mbit/s	54 Mbit/s
Control rate	1 Mbit/s	6Mbit/s
Air propagation delay	3 ns	3 ns
Optical fiber length	0 - 13 km	0 - 13 km
Payload Size (UDP)	1472 bytes	1472 bytes

We reproduced the same scenario in ns-3 thanks to our 802.11 RoF implementation. Figure 6 shows that our results are very close to those obtained in Opnet with the same parameters.

Since this scenario is quite simple (single user and no error on the channel), it is also possible to predict theoretically the expected throughput. In this case, it can be computed as a function of the delay F introduced by the optical fiber, considering the payload size and the time needed for a complete transaction to transmit one packet when there is no fiber in the network ($T_{F=0}$):

$$\text{Throughput(F)} = \frac{\text{Payload}}{T_{F=0} + (2 \cdot F)} \tag{2}$$

In the last mathematical expression, the factor 2 comes from the fact that both data packets as well as 802.11 acknowledgement packets are affected by the optical propagation delay. Using the simulation parameters of table 1 and the standard values defined in IEEE 802.11b/g, we obtain the following analytical expressions to compute the throughput for a given optical propagation time:

$$\text{Throughput}_{802.11\text{b}}(\text{F})[\text{Mbit/s}] = \frac{1472[bytes] \cdot 8}{1957[\mu\text{s}] + F[\mu\text{s}]} \tag{3}$$

$$\text{Throughput}_{802.11\text{g}}(\text{F})[\text{Mbit/s}] = \frac{1472[bytes] \cdot 8}{393.5[\mu\text{s}] + F[\mu\text{s}]} \tag{4}$$

Those theoretical expressions are plotted in figure 6 (802.11b RoF) and in figure 7 (802.11g RoF), and are compared to the results achieved with our simulator. We observe that the theoretical curves are close to our simulation curves. Since all plots have identical slopes and are close to each other, it demonstrates that the effect of the RoF transmission on the 802.11 MAC performance is well modeled in our ns-3 implementation.

5. SIMULATION RESULTS

Since the interests of RoF deployments is to use architectures with several distributed antennas, we provide in this section an example simulation using a RoF DAS with multiple RAUs and multiple stations. When multiple RAUs are driven by a single AP, two scenarios can be considered. A first scenario concerns the case where the coverage areas of the RAUs do not overlap with each others. In such scenario, the stations accessing each RAU are hidden from the stations accessing another RAU. Another scenario observed in RoF configurations concerns the case where the coverage areas of the RAUs overlap with each others. In such scenario, when a packet is transmitted by a station, the AP receives several times the same signal quite close in time and in power (simulcast). However, the current Wi-Fi receiver implementation in ns-3 is not able to handle simulcast scenarios. As a result, the current receiver model should be extended to enable the simulation of those overlapping configurations.

In the scenario where the coverage areas do not overlap, all groups of stations are hidden from each other since RAUs are located in clearly spaced areas. We reproduced such sce-

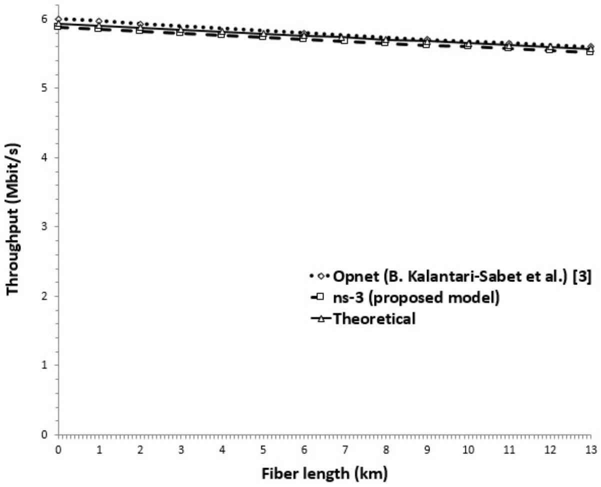

Figure 6: Comparison between results achieved with our model implemented in ns-3 and the results obtained with Opnet and with an analytical computation for 802.11b RoF.

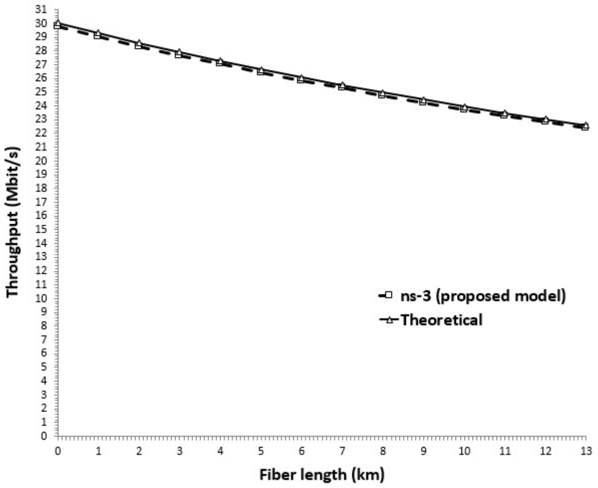

Figure 7: Comparison between results achieved with our model implemented in ns-3 and the results obtained with an analytical computation for 802.11g RoF.

nario in ns-3 using our RoF model with a DAS configuration where four RAUs are distanced of one kilometer around a single AP, each RAU being accessed by one station (figure 8). As all antennas are placed far enough from each other, the received signals from other RAUs are much lower than the receiver sensitivity. Consequently, each station receive only once all frames transmitted by the AP and do not hear the traffic sent by other stations.

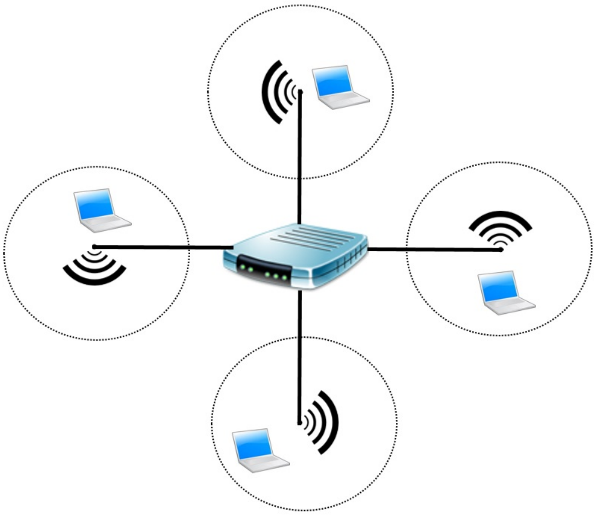

Figure 8: RoF DAS configuration without overlapping considered in the example simulation.

Since the stations are hidden from each other, we compare the simulation results obtained when the IEEE 802.11 RTS/CTS (Request To Send / Clear To Send) mechanism is enabled and when the RTS/CTS mechanism is disabled. In our simulations, we considered a continuous upstream traffic transmitted by all the stations and the parameters were set as previously (table 1). As it had been demonstrated in [6], the simulation results obtained with our implementation (Table 2) confirms that the RTS/CTS access performs better than the basic access in the hidden nodes scenario in RoF DAS. Those simulations has been limited to the case of IEEE 802.11b and IEEE 802.11g, since there is no IEEE 802.11n model in the current ns-3 version.

Table 2: Aggregated throughput obtained in example simulation.

	Basic Access	RTS/CTS Access
IEEE 802.11b	0.64 Mbit/s	2.41 Mbit/s
IEEE 802.11g	1.03 Mbit/s	5.38 Mbit/s

6. CONCLUSION AND PERSPECTIVES

Our research work consists in the evaluation and the optimization of the MAC layer performance in RoF systems. To achieve this study in the case of IEEE 802.11 transmissions, we decided to work with ns-3 since it includes a rather complete Wi-Fi model. However, the simulator doesn't include any support for simulation of RoF networks. In this paper, we provide a radio-over-fiber model in ns-3 which can be used to quantify the IEEE 802.11 MAC layer performance of any RoF configuration.

Our proposed model has been validated by comparing the simulation results with theoretical computations and with results obtained by other working groups with Opnet simulator. Furthermore, we showed that our model supports the simulation of RoF DAS when the multiple antennas are placed in clearly separated areas.

The development of our 802.11 RoF simulation model is still ongoing. In order to support the simulation of RoF DAS with coverage overlapping, the main improvement will be to extend the receiver model to handle with simulcast conditions. In addition, since optical network components are being developed for ns-3, our model should integrate those modules in order to provide a more accurate optical channel model. Moreover, as IEEE 802.11n version is presently under development in ns3, it should be possible to evaluate the performance of the 802.11n RoF networks in the next future.

Up to now, we considered the case of 802.11 radio signals and we added RoF components to the existing Wi-Fi model of ns-3. As a perspective, we propose to develop a protocol-independent RoF model so that a same model could be used for different wireless protocols (Wi-Fi, ZigBee, WiMAX, ...).

7. ACKNOWLEDGMENTS

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